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EVALUATION OF DRAINAGE FOR SALINITY CONTROL IN GRAND VALLEY

G. V. Skogerboe, et al

Colorado State University

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Irrigation return flows in the Grand Valley of Western Colorado contribute to the serious salinity problems in the Colorado River Basin by carrying large salt loads resulting from contact with local saline soils and aquifers. Since the valley is one of the more significant salt sources, it is therefore a logical area for evaluation of the effectiveness of various salinity control measures. This study has emphasized two on-farm control alternatives, namely, irrigation scheduling and field drainage. The contents of this report consider the latter measure. Three farms were extensively studied during the 1972 and 1973 irrigation seasons to identify drainage needs and the effect field relief drainage would have on reducing salinity in the return flows. During the spring of 1973, a perforated plastic pipe drainage system was installed on one of the farms. Each farm was then incorporated into an irrigation scheduling program. The results indicate that while field drainage is effective in skimming water off the top of the water table where salinity concentrations are typically 20%-30% less saline, the high costs emphasize the need to reduce seepage losses by lining canals and minimize deep percolation losses through improved on-farm water management in order to minimize the requirements for drainage facilities.

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EVALUATION OF DRAINAGE FOR SALINITY CONTROL IN GRAND VALLEY

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Irrigation return flows in the Grand Valley of Western Colorado contribute to the serious salinity problems in the Colorado River Basin by carrying large salt loads resulting from contact with local saline soils and aquifers. Since the valley is one of the more significant salt sources, it is therefore a logical area for evaluation of the effectiveness of various salinity control measures. This study has emphasized two on-farm control alternatives, namely, irrigation scheduling and field drainage. The contents of this report consider the latter measure.

Three farms were extensively studied during the 1972 and 1973 irrigation seasons to identify drainage needs and the effect field relief drainage would have on reducing salinity in the return flows. During the spring of 1973, a perforated plastic pipe drainage system was installed on one of the farms. Each farm was then incorporated into an irrigation scheduling program. The results indicate that while field drainage is effective in skimming water off the top of the water table where salinity concentrations are typically 20%-30% less saline, the high costs emphasize the need to reduce seepage losses by lining canals and minimize deep percolation losses through improved on-farm water management in order to minimize the requirements for drainage facilities.

English units are used throughout this report. For English to Metric conversion, refer to the table of equivalents in the SECTION XI.

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SECTION I

CONCLUSIONS

Drainage investigation in the Grand Valley began shortly after the turn of this century when local orchards began failing due to saline high water tables. Study showed the soils to be not only saline but also having low permeabilities. At the time, the future development of the Bureau of Reclamation's "Grand Valley Project" loomed as a severe threat to the low lying lands between it and the Colorado River. In answer to these drainage needs, the solutions were clearly set forth but never fully implemented because of the large capital investment required. However, the citizens of Grand Valley did elect to form a drainage district supported by a mill tax levy in order to construct open ditch drains and some buried tile drains to correct trouble spots.

The construction of open drains has played an important role in Grand Valley. These drains serve as outlets for tile drainage systems, as well as intercepting and conveying tailwater runoff which would otherwise flow over surface lands, infiltrate, and contribute to additional subsurface groundwater flows, subsequently reaching the Colorado River with increased salt pickup.

This study was undertaken with the history of local drainage well in mind, but for a different purpose--that being the skimming of water from the top of the water table before it reaches equilibrium with the highly saline soils and aquifers below, as well as demonstrating to local farmers the benefits in increased crop production by improved drainage.

Three farms were selected for drainage investigations during the 1972 irrigation season. The studies showed that the drainage problems on two of the farms could be alleviated by improved on-farm water management. In particular, increasing irrigation efficiency during the early season would sufficiently reduce deep percolation losses, which in turn would keep the groundwater level at a satisfactory depth below the ground surface to allow good crop production.

The results from the two farms illustrate the adage--"an ounce of prevention is worth a pound of cure". Thus, the first steps in a salinity control program are to minimize: (a) seepage losses from canals and laterals; and (b) deep percolation losses from croplands (ideally, the deep percolation losses would not exceed the leaching requirement). By minimizing the amount of moisture reaching the groundwater, the requirements for field drainage will also be minimized.

The third farm had been originally selected for investigation as an example of the worst conditions encountered in Grand Valley. An 11.6-acre (4.7 hectares) field on this farm was selected for construction of a field drainage relief system. Besides having a very high groundwater level, the soils have low permeability, high salt content, and the topography is irregular. In order to correct these deficiencies, the following measures were taken: (a) a drainage system consisting of 4-inch diameter (10.2 centimeters) perforated corrugated plastic pipe was installed on 40-foot (12.2 meters) centers at an average depth of 6 feet (1.8 meters); (b) the field was leveled to allow better surface irrigation; (c) the field was plowed to a depth of 2 feet (60.1 centimeters) to increase surface permeability; and (d) the field was planted in salt tolerant Jose Tall Wheatgrass with a cover crop of oats.

Studies of the three farms, plus two additional farms investigated for irrigation scheduling, show that field drainage effluents had a salinity averaging 3000 mg/l less than the present subsurface irrigation return flows reaching the Colorado River.

A principal advantage of field drainage (e.g., tile of perforated pipe) is that the effluent is a point source which can then be placed into a collection system for disposal (e.g., evaporation ponds, deep well injection, or desalination). Drainage in conjunction with salt disposal would be required to achieve a zero discharge policy for irrigation return flows.

As part of this study, an alternative use of drainage was considered. During the 1950's, pump drainage from the deep cobble aquifer was tested and proved most effective for reclaiming croplands. By itself, pump drainage offers no salinity control benefits because the salinity of the pump drainage effluent is comparable to the salinity of subsurface irrigation return flows reaching the Colorado River. Pump drainage in combination with desalination would be effective in reducing salt loads returned to the river. In determining the costs of pump drainage in combination with desalting, it becomes apparent that this alternative is quite costly. However, with the recent advances in desalination technology, this alternative method of decreasing salt loads of river systems is certain to become increasingly feasible as time progresses. This control measure would likely be considered as the final step in an overall salinity control program, which would only occur at some time in the future.

SECTION II

RECOMMENDATIONS

Monitoring should be continued on the Wareham farm where a drainage system consisting of 4-inch (10.2 centimeters) diameter perforated corrugated plastic pipe was installed during the spring of 1973. In particular, the long-term benefits in skimming the less saline groundwater flows should be established, as well as evaluating the length of time required to reclaim this cropland to allow the production of higher cash value crops.

A thorough analysis of desalting technology should be undertaken as applied to reducing salt loads from irrigation return flows. Most desalination studies are geared towards producing high quality effluents for satisfying municipal or industrial water demands. For irrigation return flows, considerable economies can be realized by removing only a fraction of the total salt load (e.g., reducing salinity concentrations by one-half or two-thirds).

An overall salinity control program for Grand Valley will require a combination of canal and lateral lining, on-farm irrigation improvements, and drainage facilities. The cost effectiveness of each salinity control measure should be developed, which would relate cost of the measure to the reduction in salt load reaching the Colorado River. Then, the optimal use of drainage facilities in combination with the other salinity control measures can be established. This analysis would not only provide the cost distribution among the various measures, but would also provide guidelines as to the timing sequence for implementation.

SECTION III

INTRODUCTION

STATEMENT OF THE PROBLEM

The necessity for coordinating irrigation, drainage, and salinity control activities in arid regions of the world has been repeatedly described since the earliest times in recorded history. Relics of abandoned irrigation systems, alkali deserts, and saline water resources are evident from the Tigris and Euphrates River Basins to the Rio Grande in New Mexico and Texas. In each historical case, the rapidity with which drainage problems developed into local crises and often regional concern has been startling (Luthin, 1966).

One of the more recent cases where irrigation, drainage, and salinity have become factors in the development of water for societal needs is in the Colorado River Basin (Figure 1). The problem has taken on a new dimension in that the sources of the salinity are generally not the bearers of the damage. As a result, concerned parties from each of the seven basin states and the Republic of Mexico have become actively engaged in finding technical and political remedies for the mounting salinity concentrations.

The U.S. Environmental Protection Agency (EPA) is one of the institutions involved with managing the quality of the river flows and is the agency directed by federal mandate to alleviate water pollution problems. In response, the EPA has launched comprehensive research, development, and demonstration programs to upgrade salinity control technology to the level necessary to combat the problem on a basinwide basis.

Since a significant portion of the total salt load being transported by the river is derived from irrigated agriculture, the initial studies have been directed towards improving irrigation systems. One of the several important efforts to develop salinity control technology has been the Grand Valley Salinity Control Demonstration Project located in the irrigated confines of the Grand Valley in western Colorado (Figure 2).

THE STUDY AREA

The Grand Valley area is among the most significant sources of salinity in the Colorado River Basin. Water entering the near-surface aquifers in the valley become heavily laden with salts dissolved from the marine soils and shale occurring extensively in the area. The primary source of salt is the Mancos Shale

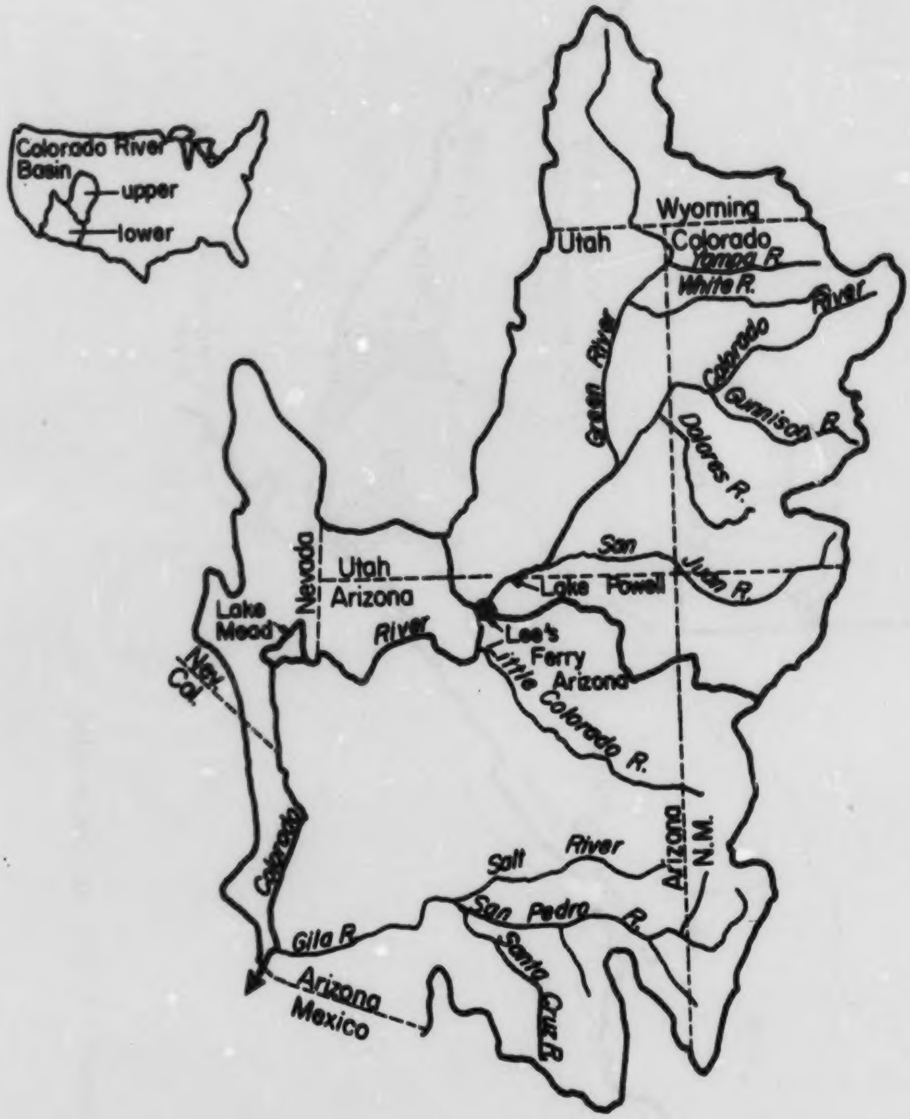

Colorado River Basin
upper
lower
Wyoming
Utah
Colorado
Yampa R.
White R.
Colorado River
Green River
Gunnison R.
Dolores R.
San Juan R.
Nevada
Utah
Arizona
Lake Powell
Lake Mead
River
Lee's Ferry
Arizona
Little Colorado R.
Nev.
Cal.
Colorado
Arizona
N.M.
Salt River
San Pedro R.
Santa Cruz R.
Gila R.
Arizona
Mexico

Figure 1. The Colorado River Basin.

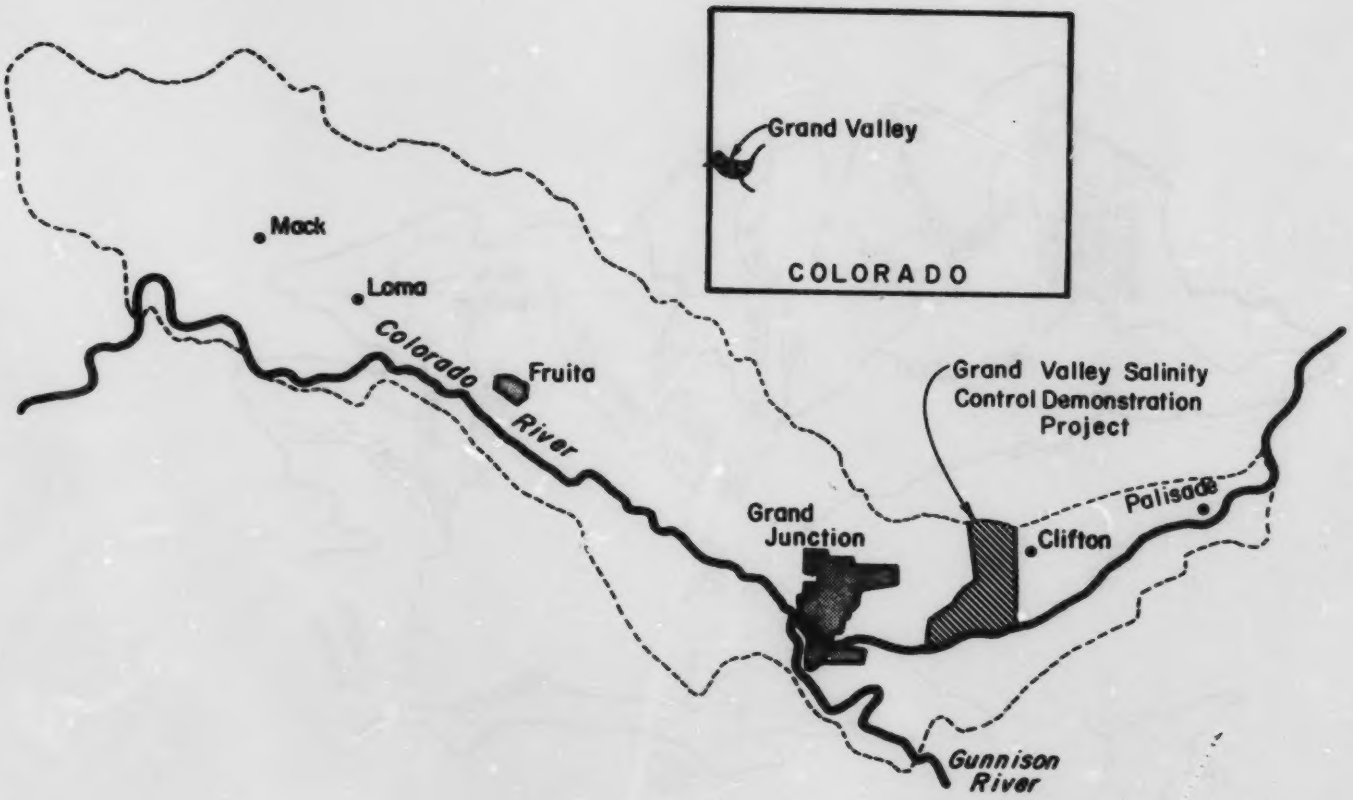

Grand Valley
COLORADO
Mack
Loma
Colorado River
Fruita
Grand Valley Salinity Control Demonstration Project
Palisade
Grand Junction
Clifton
Gunnison River

Figure 2. The Grand Valley of Colorado.

formation, which was formed by the alternate advance and recession of prehistoric inland seas once dominating the western United States. Since most of the water contacting these aquifers comes from conveyance (canals and laterals) seepage and deep percolation from overirrigation, the emphasis of salinity control technology is in improving both the conveyance (water delivery) and farm subsystems.

Agricultural Land Use

Early explorers envisioned the Grand Valley as a poor risk for agriculturally related activities because of sparce rainfall. However, the first pioneering farmers rapidly surmounted this restriction by irrigating with water diverted from the rivers entering the valley. Through a long struggle, an irrigation system evolved to supplement the otherwise meager supply of precipitation during the hot summer months (Figure 3). In time, the ageless futility of irrigation without adequate drainage was demonstrated in the valley when the low lying acreage became waterlogged with highly saline groundwater. Today, the failure to completely overcome these conditions is still evident as illustrated by a summary of agricultural land use in the valley presented in Figure 4, where most of the acreage of phreatophytes and barren soil, as well as much of the pasture acreage, is the result of drainage problems.

Irrigation Practices

Furrow irrigation is the prevalent method of applying water to croplands in the valley. Small laterals carrying one to five cubic feet per second (cfs)* divert water from irrigation company or district operated canal systems to one or more irrigators. Water then flows into field head ditches where it is available to supply the growing crops and maintain a salt balance in the root zone. The agricultural economy, consisting mainly of alfalfa, corn, sugar beet, orchard, and small grains, is served by a more than adequate water supply. In fact, the 70,830 acres of land under this type of cultivation enjoys a total diversion of more than eight acre-feet per acre during normal years. Considering that the evapotranspiration of these lands is usually less than three acre-feet per acre, it is obvious that existing irrigation efficiencies are extremely low.

The variation in the local climate separates the agricultural setting into three primary regions. In the eastern

*For conversion to metric units, see SECTION XI.

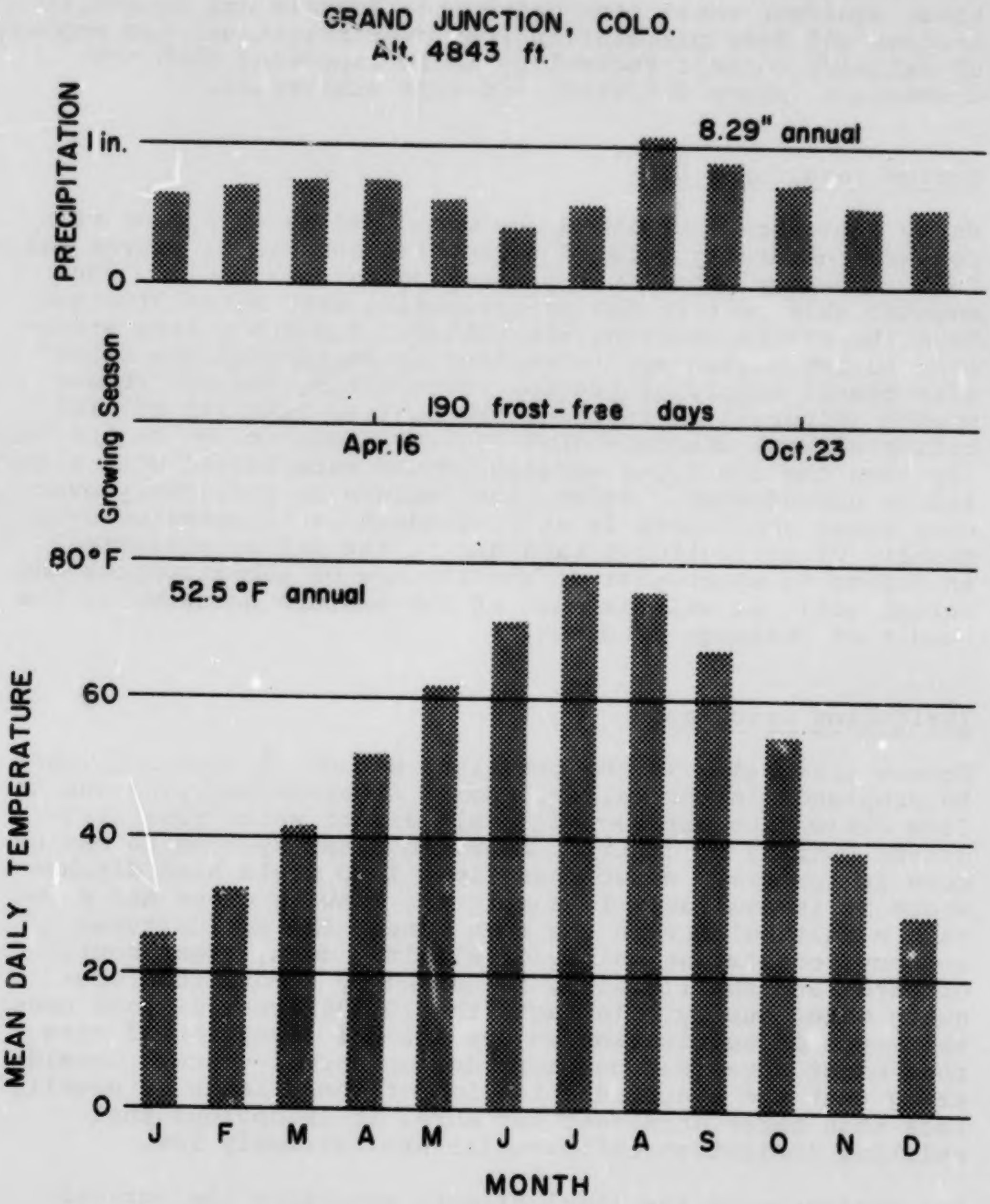


Figure 3. Normal precipitation and temperature at Grand Junction, Colorado.

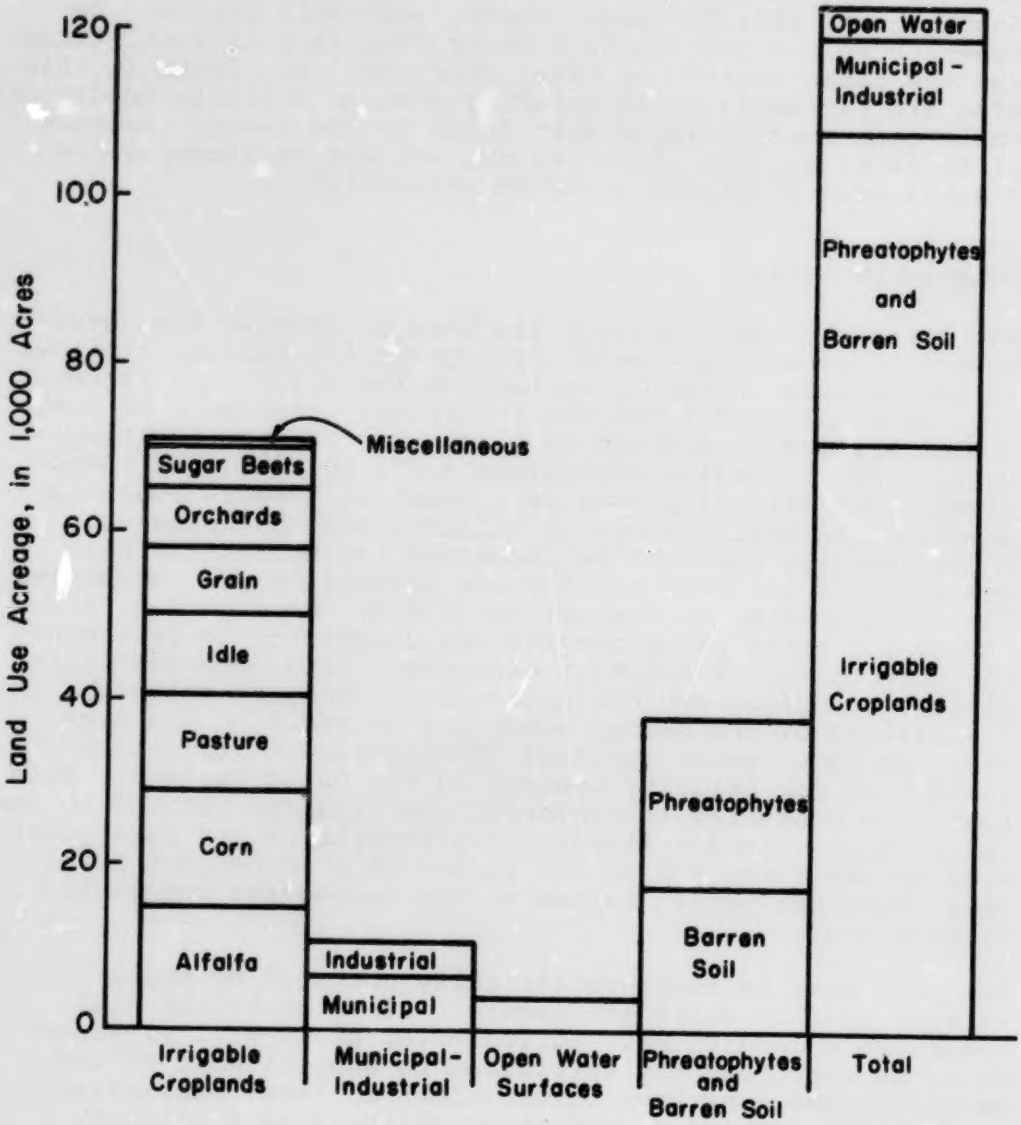


Figure 4. Agricultural land use in the Grand Valley (Walker and Skogerboe, 1971).

end of the valley, the protective proximity to the abrupt Grand Mesa results in some extension of the growing season, allowing apple, peach, and pear crops to mature. In the western part of the valley, the primary emphasis is on producing corn, alfalfa, sugar beets, and small grains. Between these two regions is a transition zone of small farms and the urban setting of Grand Junction. The farms in this area are particularly affected by adverse drainage conditions while contributing large salt loads to the river. Because of these conditions, this project was set up encompassing a small area within this region (Figure 2).

PURPOSE OF STUDY

The purpose of this project has been to further the development of technology needed to improve the quality of flows in the Colorado River by evaluating the effects of improving both structural and non-structural components of irrigation systems as a means of minimizing groundwater flows contacting the saline subsurface soils and geologic formations. The initial phases were begun in 1968 to evaluate canal and lateral linings as salinity control measures. Those results, reported by Skogerboe and Walker (1972a), demonstrated the need for further investigations concerning the on-farm water management practices. As a result, a second and third phase program was undertaken to determine the feasibility of two farm management improvements--irrigation scheduling and drainage--in controlling salinity. The results of the second phase are reported in the previous project report entitled "Evaluation of Irrigation Scheduling for Salinity Control in the Grand Valley". This report is presented to summarize the findings related to the third phase, field drainage. The experience and data generated by the first and second phases of this project have been important prerequisites to the successful conclusion of this study.

The test area is characteristically operated by small unit farmers and the soils are severely affected by the high water table conditions. Agricultural productivity, therefore, is not presently sufficient to support most of the occupants and many have outside jobs in local businesses or industry. Besides evaluating drainage as a salinity control measure, one of the concerns of the investigators was in demonstrating the benefits of drainage to the individual land owners. These lands were once among the valley's most productive (at the turn of the last century) and a significant impetus could be generated locally in support of salinity control programs if such a measure was instrumental in increasing agricultural productivities of these salt-affected lands.

SCOPE OF THE STUDY

Five fields in the area, located in Figure 5 and described in Table 1, were incorporated in the study to represent a cross-section of agricultural practices in the Grand Valley. Three of the farms (Kelleher, Canaday, and Wareham farms) were included primarily as part of the drainage investigations, while the remaining two (Bulla and Martin farms) were specifically used for evaluating irrigation scheduling.

During the 1972 irrigation season, irrigation practices were monitored on the Kelleher, Canaday, and Wareham farms. Then, during the spring of 1973, a perforated plastic pipe drainage system was constructed on the Wareham farm. All three farms were then incorporated into the irrigation scheduling program during the 1973 irrigation season, which was done cooperatively with the U.S. Bureau of Reclamation (USBR) valley-wide irrigation scheduling program, thereby strengthening the results of both studies. At the same time, drainage outflows were monitored from the Wareham farm.

In addition to the drainage-related evaluations, data collection and analysis activities relative to the important hydro-salinity parameters in the test area were maintained to provide continuity with earlier data. The investigators concluded that such efforts were necessary to detecting any changes relative to the improvement of water management practices in the area and to refine the results of the earlier studies, if desired. Of course, the size, scope, and detail with which any research effort is conducted must be compromised with time, talent, and funding provided to the researchers. A workable balance was achieved in this project while maintaining a high degree of sensitivity towards the goals of the project.

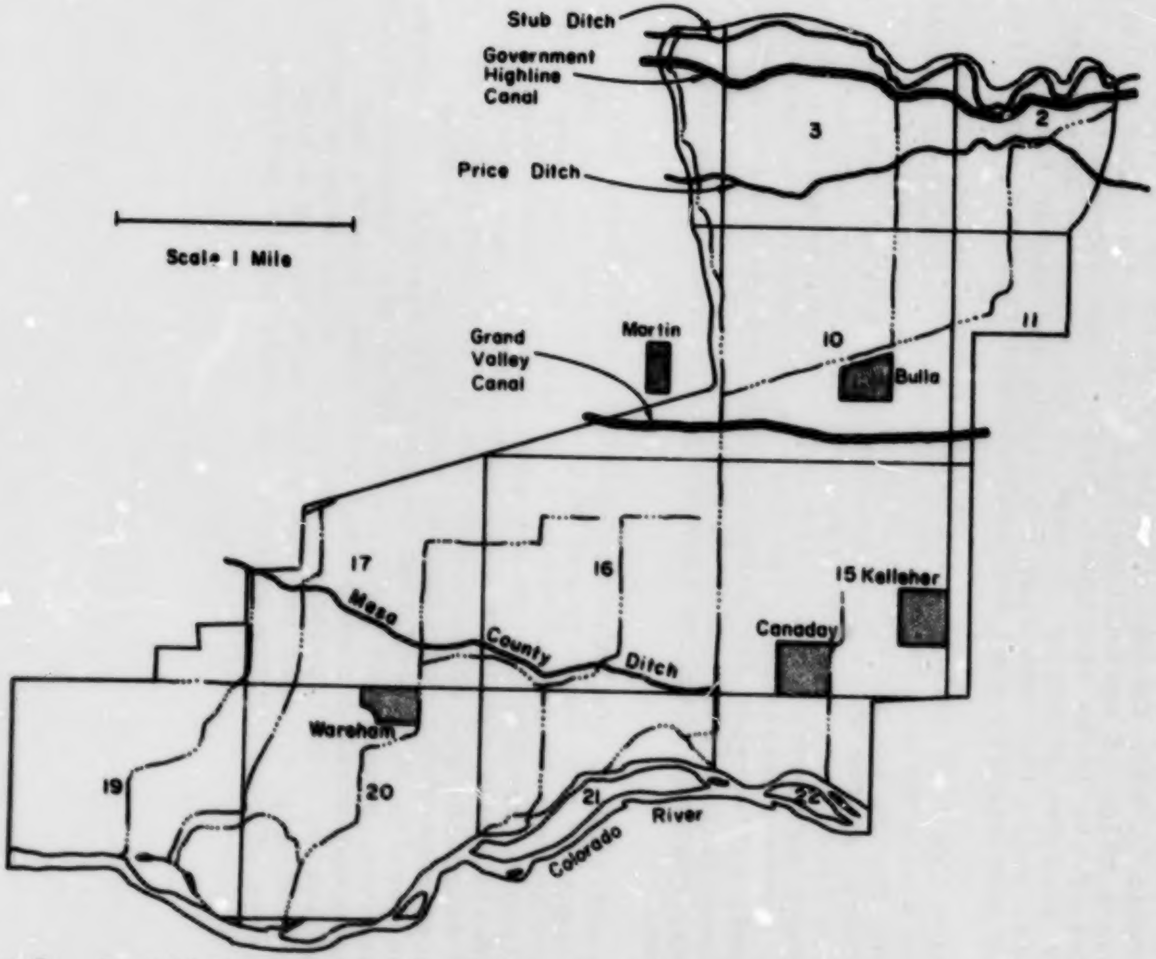

Stub Ditch
Government Highline Canal
Price Ditch
Scale 1 Mile
Grand Valley Canal
Martin
10
Bulla
11
2
3
17
16
Mesa County Ditch
15 Kelleher
Canaday
Wareham
19
20
21
22
Colorado River

Figure 5. Location of study farms in demonstration area.

Table 1. DESCRIPTION OF FARMS IN THE DEMONSTRATION AREA INCLUDED IN THE DRAINAGE AND IRRIGATION SCHEDULING STUDIES

Farm	Crop	Crop Acreage	Field Capacity	Wilting Point
Martin	Corn	9.2	22.3	10.7
Bulla	Barley	10.7	24.2	13.4
	Corn	15.0	23.9	12.1
Canaday	Barley	17.1	26.5	12.8
Kelleher	Oats	9.8	25.0	12.2
	Pasture	1.0	25.8	14.1
Wareham	Alfalfa	17.4	30.5	16.7
	Crested Wheatgrass	13.6	29.3	16.7

SECTION IV

PREVIOUS DRAINAGE INVESTIGATIONS

GENERAL

The inadequacy of both natural and man-made drainage systems in the Grand Valley have been repeatedly demonstrated by high water tables, flooded basements, and insect problems. During the final two decades of the last century, the local soils supported an agricultural system of orchards, forage crops, small grains, and gardens. By about 1905, however, there began to be an increasingly significant acreage affected by poor drainage and crop production began to decline. Efforts to remedy these conditions were often off-set by additional acreages being irrigated, especially after the implementation of the Grand Valley Project of the Bureau of Reclamation. Today, almost 30% of the irrigable acreage in Grand Valley supports only marginal valued pasture, hay, and grain fields.

Drainage in the valley has passed through three major eras. First, as the early drainage problems were encountered between 1890 and 1908, the U.S. Department of Agriculture conducted extensive surveys to define the cause of the problems. Results of that first study formed the basis for the second period between 1915 and 1945 when the Grand Junction Drainage District evolved. Finally, the interval between 1945 and 1960 marked a period of specialized study instigated to evaluate specific drainage and land reclamation alternatives.

In this section, it is the intention of the authors to summarize the findings of these periods as a means of correlating them with the results of this study.

EARLY DRAINAGE INVESTIGATIONS

The high salinity content of the substrata and the lack of natural drainage were quickly recognized as the major drainage problems in the Grand Valley. Consequently, in 1908 the U.S. Department of Agriculture through its Office of Public Roads and Rural Engineering initiated local drainage studies to delineate the specific nature of the problem and suggest appropriate remedies (Miller, 1916).

This study encompassed the valley lying north of the Colorado River between Palisade and Loma. At the time, the most predominant agricultural enterprise was the fruit industry which also exhibited the first signs of rising groundwater levels. This period pre-dated the construction of the

Government Highline Canal, indicating that conditions would worsen and a solution would be needed in the immediate future.

To accomplish the goals of the project, research was conducted in four major areas: (1) nature and characteristics of the soils and subsoils; (2) groundwater; (3) local salinity problems; and (4) description of the irrigation waters.

Nature of Local Soils

Silt and clay constitute the principal elements of all the soils except in what is known as the Billings fine sandy loam which primarily contains very fine sand. Even though these soils are often difficult to till and crust readily if flooded during irrigation, they are nevertheless very productive.

Miller (1916) found that most of the soils examined were deep and relatively uniform in nature through the upper soil profiles. An underlying gravel aquifer was identified throughout much of the area ranging in depth below the soil surface from five feet to more than 30 feet. As a means of establishing the physical dimensions of the cobble aquifer, fifteen experimental wells were drilled to the underlying shale, and information was collected from local residents who had installed wells to water livestock.

Groundwater

The groundwater levels in the Grand Valley area have been steadily rising since irrigation was introduced. They had also been increasing in salt content during this interval, with concentrations at the time of the study of about 10,000 ppm in some localities. The salinity consisted of about 60 percent sulfates, 30 percent chlorides, and 10 percent bicarbonates and nitrates. In the early history of the valley, it was common practice to dig wells to the underlying gravel in order to obtain domestic and stock water during the winter months when the canals were shut down. As irrigation increased, the water from many of these wells became so badly alkaline as to be entirely unfit for human drinking purposes and generally so for stock. By the time Miller's study was initiated, only a few wells at either end of the valley were in use.

Salinity Conditions

In connection with the work that was being conducted by Miller (1916) in the valley, a total of 392 soil samples were collected from 22 tracts of land lying north of the Denver and Rio Grande Railroad line between Clifton and Fruita. The samples, which were submitted to the U.S. Bureau of Soils for analysis, indicated an average constituent content of: (1) calcium sulfate or gypsum, 49.5 percent; (2) sodium chloride or common salt, 13.6 percent; (3) sodium sulfate or Glaubers salts, 10.4 percent; (4) magnesium sulfate or Epsom salts, 9.7 percent; (6) calcium chloride, 2.1 percent; (7) magnesium chloride, 1.6 percent; and (8) nitrates, 2.1 percent. A reclassification of the above results gives: (1) gypsum, 49.5 percent; (2) sulfates, other than gypsum, 20.1 percent; (3) chlorides, 17.3 percent; (4) bicarbonates, 7.5 percent; and (5) nitrates, 2.1 percent.

Quality of the Irrigation Water

Irrespective of the action of capillarity as a factor in the accumulation of the alkali salts in certain soils of the Grand Valley, due consideration was given to the quantities that may have been deposited through the application of irrigation water. The nature of the salts in the Colorado River at this time did not differ markedly from data being collected today.

Recommendations

The primary recommendation from the study was to construct an open drain system that would penetrate the underlying cobble aquifer. In addition to the open drain system, it was proposed that tile lines running north and south through the area and spaced at 1/4 mile intervals should be installed. It was felt at this time that the system described above would provide a workable solution to the drainage problem in the area.

The cost of such a system was, at best, difficult to estimate, but using construction cost figures in 1916 the average per acre cost was somewhat less than $35.00.

In his summary, Miller (1916) made the following statement. "The drainage of much of the land of the valley is practicable only under community organization, and not then unless a thorough system of drainage be installed in accordance with plans based upon full knowledge and appreciation of the underlying conditions." Although the construction of Miller's drainage plan was not immediately undertaken as suggested, no doubt he had much to do with the formation of the Grand Junction Drainage District.

GRAND JUNCTION DRAINAGE DISTRICT

By 1915, the fact that the drainage problem was almost valley-wide and the realization that the upper lands and canals contributed to the lowland problem were generally accepted. With the plans for the construction of the Government Highline Canal nearing approval, valley residents in accordance with the recommendations of Mr. Miller began thinking of a valley-wide drainage system. On September 7, 1915, a three member board of directors met in Grand Junction to organize a drainage district. Business included the election of Gus. J. Johnson as president of the Board and the selection of "The Grand Valley Drainage District" as the name of the organization. Following this meeting, the proper legal papers were drawn up and sent to the State Capital for approval and formal recognition of the district. In November of 1915, the Drainage District contracted with the U.S. Department of the Interior to conduct a feasibility of the drainage possibilities, including a plan with an accompanying cost estimate.

On April 24, 1917, the Board of Directors received notice that the preliminary study had been completed and a tentative design formulated. The letter also revealed that the system would cost approximately 1.7 million dollars which because of budget restrictions could not be financed by the Federal Government. To a valley with a population of less than 12,000, the thought of raising this much money was staggering, thus making the full-scale drainage system impossible. As an alternative, a much smaller project was proposed. Since the Highline Canal currently under construction would need wasteways for unused water, the Government suggested that many of the natural washes be combined with man-made wasteways at such a depth as to remove the waste water and provide some lowland drainage. Although the cost was still almost $300,000, it was connected with the Federal irrigation project and thus could be financed through existing arrangements. Under this proposal, the Drainage District was responsible for providing rights-of-way for all proposed drains and lifetime maintenance of all channels.

The need for a method of obtaining revenue for the District was now apparent. On May 21, 1917, the proposition to assess the land owners in the valley based on the benefits to be received was presented. Provisions were made on May 29, 1917, to obtain the needed data which included the name and address of each land owner, a description of the land owned, and an estimate of the benefits to be derived from the project. This information was then published by the District, along with the estimated benefits to each piece of land. A period during which the land owners could formally contest the estimated benefits was designated. Having dealt with all protests, the District made the first assessments on the land in the district on September 14, 1917.

Further negotiations with the Government resulted in a new cost-sharing proposal on the smaller scale drainage project. Under the new proposal, the Drainage District was to pay 40% of the right-of-way fees and 40% of the channel maintenance cost. These costs could be repaid over a ten-year period at no interest, but at the end of the 10-year period a new maintenance agreement would have to be developed. In addition, if the District could not repay the debt in the 10-year period, the loan could be extended at an interest rate of 6% per annum. This proposal was approved by the Board of Directors and a special election called for November 19, 1917, at which time the contract was approved and signed.

Once the method for securing operating funds and entering into the first construction contract with the Federal Government had been resolved, the Drainage District began formal operation. Many agreements for rights-of-way were made and channels constructed during the period from 1918 through 1923. The size of the system to be maintained grew to the extent that superintendents were needed to handle the work. Thus, on February 12, 1921, M.G. Goucher and A.A. Jones were hired as superintendents of maintenance and construction.

On June 6, 1923, the name of the organization was changed to "The Grand Junction Drainge District" by a vote of the people. Provisions were also made for regular elections for members of the Board of Directors.

August 1, 1923, is possibly the most important date in the history of the District. Faced with the task of enlarging the drainage system, the District encountered the critical question of how to raise the needed capital. Many suggestions for obtaining capital were put forth and two of them, namely, selling bonds and a tax mill levy, were placed on the ballot of a special election held on this day. Fortunately for the drainage program in Grand Valley, the people voted in favor of the mill levy. The tax levy was set at 4 mills, which in 1923 amounted to approximately $70,000, for operation of the Drainage District.

Thoughts again centered on a major full-scale drainage system for the valley. The Reclamation Service plans were revived and modified. A call for bids went out on December 11, 1923, and the low bidder was the Winterburn and Lumsden

Construction Co. The contract was signed and construction began on a major open channel drainage system which comprises much of the present day drainage system.

The present boundaries of the District are shown in Figure 6. The District has approximately 400 miles of open channel and 150 miles of tiled drains within its boundaries. The open channels are quite evenly dispersed throughout the valley, whereas most of the tile lines are found under the orchards near Palisade. With current policy, the District handles the construction of open drains and installation of tile drains, as well as normal maintenance on all drains after construction, at no cost to the farmer. The farmers are required to provide the rights-of-way for open drains and all materials used for tile drains (gravel and pipe). It is interesting that the specifications used by the District are the same ones used on the original Government contracts, although some limited modifications to bring them up to date have been included.

RECENT DRAINAGE INVESTIGATIONS

Drainage investigations in the Grand Valley have been conducted almost continually since the work of Miller in the early 1900's and the subsequent formation of the Grand Junction Drainage District. With the advent of World War II and the need for higher crop production, the value of irrigated land greatly increased. This brought forth a new call for improved drainage in the valley, along with a willingness for both individual and Government funding. In answer to this call came renewed effort by Government agencies to solve the problem. A committee was formed which included members from the Soil Conservation Service; Bureau of Plant Industry, Soils, and Agricultural Engineering (BPIS&AE); and Colorado A&M College. A summary entitled "Progress Report on Drainage Project, (1945 to Jan. 1951), Lower Grand Valley S.C.D., Mesa, Co., Colorado," was prepared in July, 1951, by Rey S. Decker, Head, Regional Drainage and Earth Testing Section of the S.C.D. (Decker, 1951).

Initial Investigations

A project area was selected for intensive study in a locale about five miles northwest of Grand Junction, covering about 4500 acres. A community known as Appleton was located along the east central boundary of the project area, an area that was also included in the Miller study in 1908.

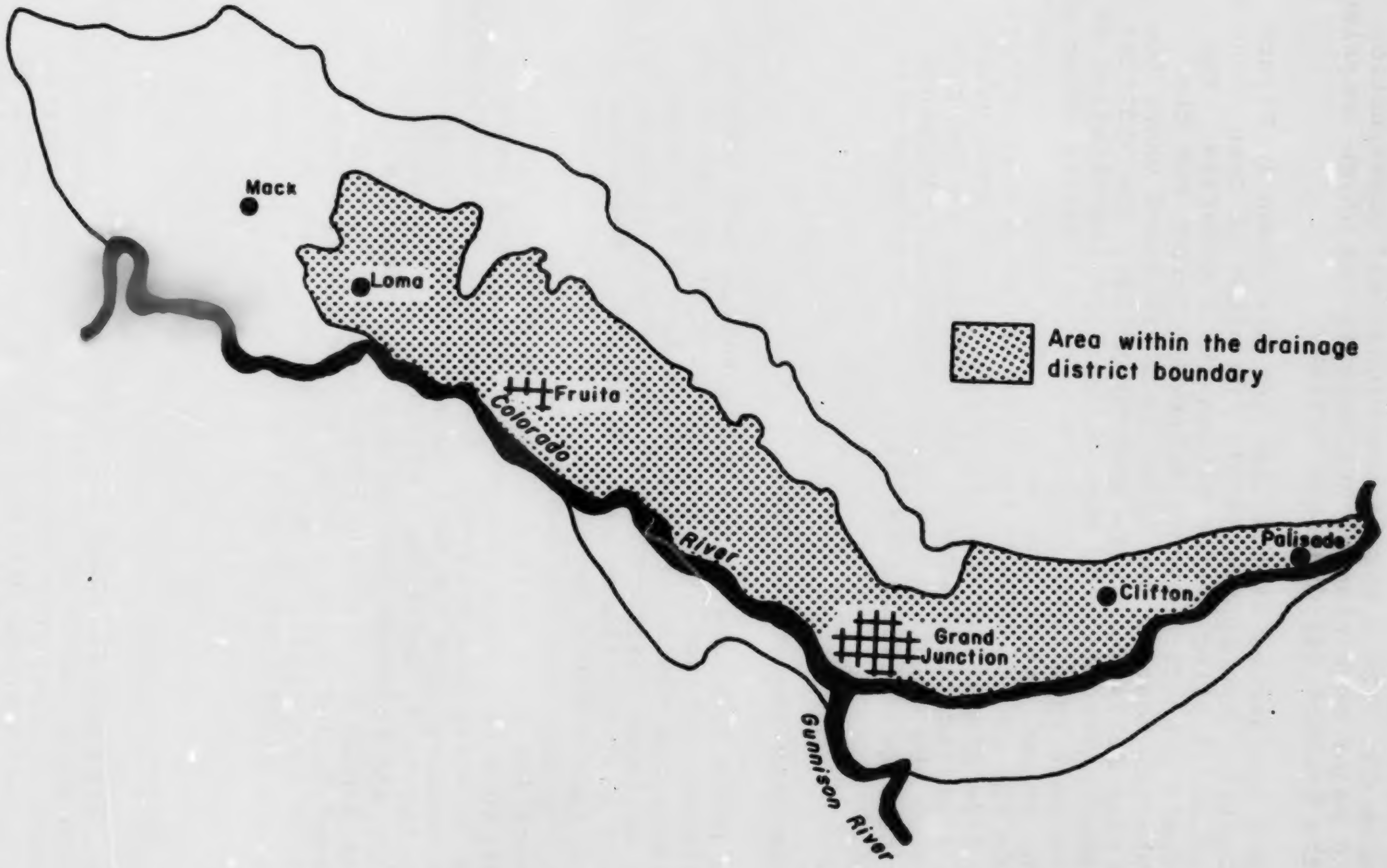

Mack
Loma
Fruita
Colorado
River
Grand Junction
Clifton
Palisade
Gunnison River
Area within the drainage district boundary

Figure 6. Boundaries of Grand Junction Drainage District.

This area contained a number of apple orchards at the time of Miller's study, but by 1945 there were no commercial orchards remaining.

A number of drains had been installed in the area during the period 1924-1945 by the Grand Junction Drainage District. While these drains provided an outlet for field tailwater and surplus irrigation diversions, they were not particularly effective in alleviating the drainage problem in the project area. It was not uncommon to find the water table within a few inches below the ground surface of the surface observation wells located on the banks of deep 8 foot - 10 foot drains. Some drains located near the river, where gravel could be tapped, appeared to function satisfactorily as was predicted by Miller (1916).

At the time of these later investigations, it was difficult to fully evaluate the effectiveness of the existing drainage system. According to Miller (1916), the water table was rising in 1916, and yet in 1945 it was at nearly the same level as in 1916. The system evidently prevented any additional rise in water table levels and undoubtedly benefited the remaining cultivated acreage.

The Soil Conservation Service (SCS) drainage investigations were initiated in early 1946 through a request for assistance. A farm known as the Willsea farm, located in the south central portion of the project area, 1 mile south and 1/2 mile west of the Appleton corner, was selected for intensive study. Conditions on the 160 acres were severly salt affected and most of the land had been abandoned.

A number of piezometers were installed on the farm in early 1946. Dr. Fireman and Mr. Reeves, U.S. Regional Salinity Laboratory, were working in the area during the summer of 1946 in connection with the B.P.I.S. & A.E. and Colorado A&M soil survey and became interested in the Willsea project. Several additional piezometers were installed under their direction and the data analyzed. The results of the piezometer data indicated an upward flow condition in the area. In one case, the loss of head in the vertical direction was 3.37 feet in a vertical distance of 7 feet (from the 14 foot to 7 foot piezometers), or a vertical hydraulic gradient of 0.48 feet. Information indicated that the water is brought into the area through the underlying cobble aquifer at a depth of between 14 and 21 feet. Since the subsurface soils had such a low hydraulic conductivity, the surface drains, which range in depth from 10-12 feet, were ineffective in removing the upward flow of water.

The possibility of pump drainage to relieve the vertical gradients in the area was considered early in 1947. In April, 1947, an 8 inch well was drilled by Mr. Willsea. The drillers log showed the first eighteen feet were local soils, followed by three feet of sand, three feet of tight clay and ten feet of cobble and gravel. An 8 1/4 inch casing, set on the bottom of the hole, was perforated at depths of 18-20 feet and 24-34 feet. Water rose in the casing to within 6 feet of the surface and was bailed out at about 40 gallons per minute (gpm) with no apparent drawdown.

This well was tested by SCS personnel on April 5, 1947, by continuous pumping for five hours at a maximum discharge of 100 gpm. A drawdown of 12 feet was effected in about 1/2 minute, but the water level could not be lowered beyond the 18 foot depth. Also, no changes in water table elevations were measurable in piezometers 150 feet from the well at the end of the pump test.

Although the Willsea pump test was not entirely successful, the Soil Conservation District supervisors and cooperators were now aroused to the possibilities of pumping for drainage. A general plan of investigation was prepared by the regional and district offices for discussion and approval by the supervisors.

A working agreement between the Lower Grand Valley Soil Conservation District and the Grand Junction Drainage District was executed in early 1948. The area was gridded with twenty-five deep test holes to determine the depth to gravel and pressure potential. Most of these holes were 40-50 feet deep with one extending to 78 feet. Hydrostatic pressure was encountered in most holes upon contact with the gravel, and water actually flowed from many of the holes for several days or even months after they were put down.

Upon completion of the deep hole grid and analysis of the data relative to depth to gravel, hydrostatic pressure, etc., 24 sets of 3/8 inch piezometers were installed. Piezometric installations varied from sets of 2 pipes 7 and 14 feet in length to sets of 3 pipes 7, 14, and 28 feet, or longer. A total of 60 pipes (865 feet) were installed on the project. Water level readings were started in May, 1948, and continued at intervals of 2-4 weeks until December, 1949.

Due to the limitation of the jetted and augered holes, it was impossible to determine the thickness of the gravel substrata using these methods. Since the thickness of the aquifer is very important in determining hydraulic characteristics of the material, a method for determining the thickness had to be found. In order to gather this information, Mesa County, through the County Soils and Drainage Committee, provided $800 for drilling six test wells. Each well was six inches in diameter, and all but No. 6 (which was abandoned because of insufficient funds) were drilled through clay and gravel into the underlying shale to a depth of five feet. Samples were taken from all formations encountered during drilling and then were analyzed. Additionally, a number of water samples from various wells, piezometers, drains, and the rivers were collected during the summer of 1949. A summary of these sample analyses is presented in Table 2.

All investigational data collected on this project pointed to the provision for adequate drainage as the first requirement in reclamation and rehabilitation of the project area. The deep artesian aquifer under the entire area, the presence of upward groundwater flow, and the ineffectiveness of deep open drains in the area all pointed toward pump drainage as the proper method, regardless of just where and how the water enters the aquifer or what causes the variation in pressure.

Field Evaluation of Pump Drainage

With the completion of the feasibility studies and estimates, the decision was made to install a drainage well at Bethel Corners. Tentative plans for construction of the well were as follows: A 24-inch diameter well with a screen 25 feet long would be installed at the bottom of the hole and surrounded by a 6-inch gravel pack. This 25 feet is in a fine gravel and sand formation. The remaining 30 feet, which is in a heavy billings silty clay loam soil, would be cased with a 12-inch standard steel pipe. There was still some question as to the necessity or desirability of a gravel pack, but further evaluations led to its exclusion.

During the next Board meetings, the plans and financing by public subscription were approved. The Mesa County Agricultural Research Committee donated $1700, with the remaining $1800 being contributed by local business firms, banks, public utilities and service clubs. In addition, the Grand Junction Drainage District agreed to pay for the necessary power for pump operations with the Public Service Company of Colorado contributing the power line. The job was completed in the latter part of June, 1951. The drillers log and casing construction are shown in Figure 7.

Table 2. SUMMARY OF WATER QUALITY SAMPLES TAKEN FROM TEST WELLS DURING 1949 (DECKER, 1951).

Sample No.	TDS (ppm)	Calcium (ppm)	Magnesium (ppm)	Sodium (ppm)	Chloride (ppm)	Sulfate (ppm)	Bicarbonate (ppm)
1	9794	672	379	1897	860	5547	427
2	9915	700	414	1848	868	5560	425
3	2750	476	103	196	140	1525	310
4	5585	644	224	744	234	3393	346
5	1081	115	27	192	240	273	234
6	941	156	34	66	22	448	215

Sample No.	Source and Notes
1	Well 10 feet into gravel aquifer, located in deep drain near Willsea well
2	Local piezometer 6 feet deep
3	Spring at foot of Fruitridge
4	Leach water (drainage interception)
5	Colorado River at 5th Street Bridge
6	Gunnison River just north of AEC Compound

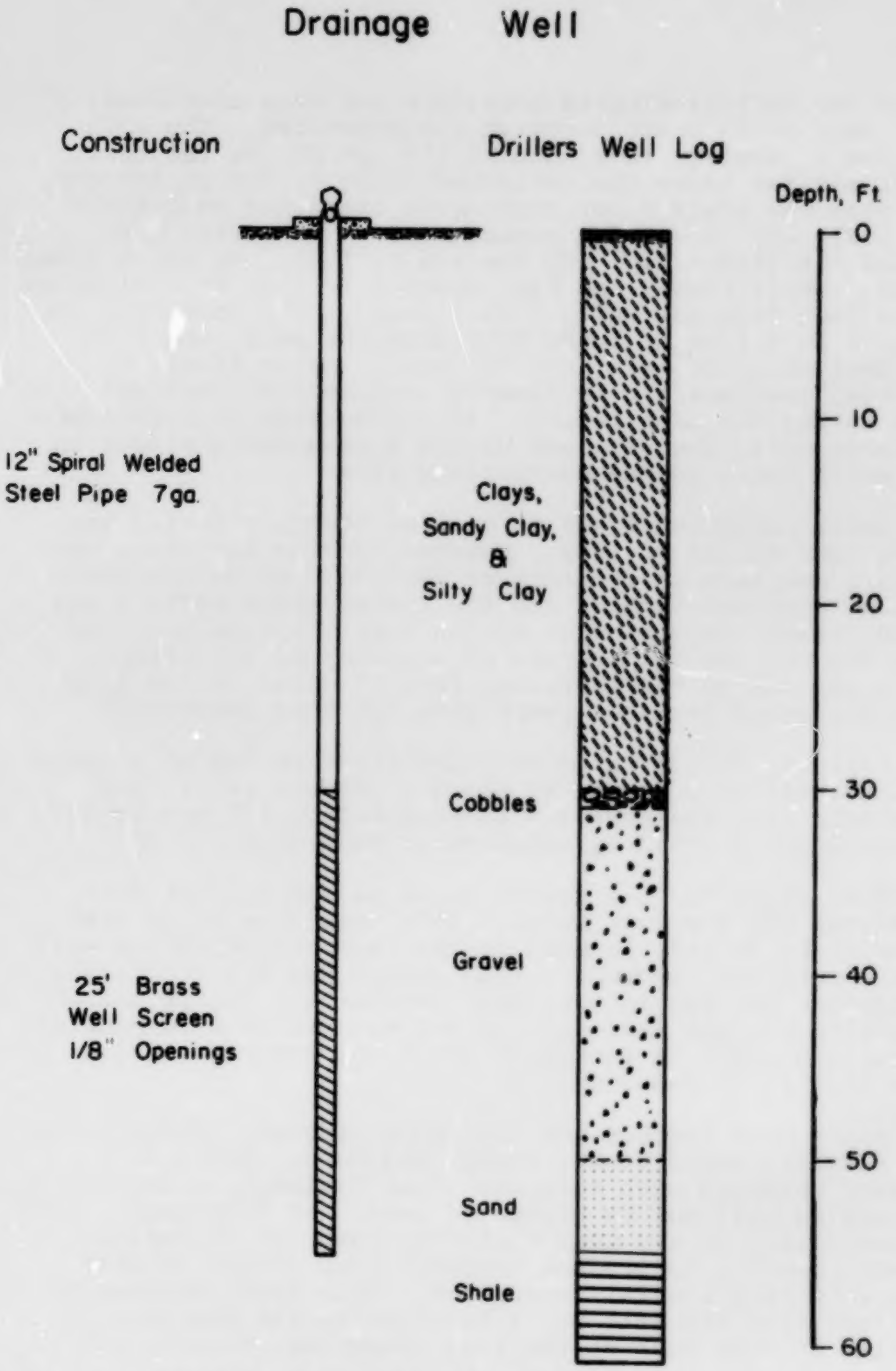

Drainage Well
Construction
Drillers Well Log
Depth, Ft
12" Spiral Welded Steel Pipe 7ga.
25' Brass Well Screen 1/8" Openings
Clays, Sandy Clay, & Silty Clay
Cobbles
Gravel
Sand
Shale
0
10
20
30
40
50
60

Figure 7. Drillers log and well construction

After the well-developing procedure had been concluded, a pump test of 30 hours duration was conducted. The well yielded an average flow rate of 250 gpm during the test, which was far below the estimated yield of 600 to 900 gpm. The pump was started for continuous operation on October 25, 1951, and except for numerous power failures, performed satisfactorily. By the end of 1951, the water level in the cobble strata had been lowered 12 feet at a distance of 50 feet from the well, 6 to 8 feet at 400 feet from the well, 1 to 3 feet at 1,600 feet from the well, and 1 to 1.4 feet at 3,200 feet from the well. Water levels in the clay loam soils were lowered between 0.22 feet and 1.50 feet during the same period. As can be seen from this preliminary data, the well was having a pronounced effect on the water table in the surrounding area.

The water table continued to decline steadily during the first four months of 1952. However, during May there was a sharp decrease in the rate of decline. Since the irrigation water was turned into the system about April 1 and field irrigation was begun during April, it was believed that the decline in the rate of lowering of the water table was due to the increased flow of water in the area. Data collected in later years bore out this assumption.

The salinity of the water over the first period of pumping remained fairly constant at about 1 percent salt. The flow rate from the pump was increased from 175 gpm to 280 gpm in March of 1952 by adjustments made on the pump.

In 1952, plans for the second stage of the project were finalized and the work began. This consisted of 16 test plots 30 by 60 feet located on the farm bordering the well in the northwest section. This ground was not completely abandoned, but was in very poor condition. The principal objective of this phase of the project was to determine if the ground could be reclaimed after the water table had been lowered by pumping.

The plots were leached and the crops planted. These included alfalfa, sugar beets, grain, and corn. Since this project entailed much more than just drainage, a detailed discussion will not be presented here. At this point, it is sufficient to say that while the pump was operating, it was possible to produce "normal" crop yields in this area with very careful management. This bears witness to the fact that the well was a solution to the drainage problem in this area at the time (Shumaker, et al., 1967).

The pump was shut off on February 14, 1955, with the almost immediate result being an increase in the head in the aquifer. The water table did not begin rising immediately since the aquifer is overlain by a dense clay layer with very low permeability. However, since this layer is not continuous, the water table was eventually affected. By the end of the growing season, the water table under the plots on the local farm had risen 3-4 feet.

The pump was used on a part-time basis until 1959, but only to protect the crop rotation plots in the land reclamation study. To the authors' knowledge, the pump has not been operated since 1960.

A drive through the area today finds the pump still there, but it is crusted with salt and overgrown by weeds. The farms that were restored to productivity have once again gone back to growing only highly salt-tolerant native vegetation. For it seems that while the method was shown to be effective, the owners of the surrounding property were either unwilling or unable to support the cost of operating the pump on the income from agriculture.

SECTION V

DRAINAGE DESIGN METHODS

The primary purpose of drainage systems for agricultural lands is to provide a soil environment including air and water which can productively support plant growth. The design of drainage systems should consider the nature of the crops, soils, climate, and local practices in order that the following basic factors in drainage be identified (Corey, 1961):

1. The depth to which the critical oxygen diffusion rate necessary for plant growth occurs;
2. The maximum allowable soil moisture content which allows the critical oxygen diffusion rate;
3. The design method for determining drain depths and spacings which incorporates the most sensitive characteristics in the soil environment; and
4. The design which accounts for special events such as long-term reclamation of the soils.

Although these basic factors represent the ideal approach to drainage, the data necessary to evaluate each factor are generally lacking and design must be made on the basis of sound judgement and previous experience.

The existing drainage design techniques have been categorized into four major approaches (Hedstrom, et al., 1971, and Corey, 1961):

1. Use of drainage coefficients;
2. Establishing an optimum water table depth;
3. Designing for a specified rate of water table decline; and
4. Incorporating a fluctuating water table system.

Each of these design approaches apply to different types of drainage conditions, and thus, the selection depends on the requirements of the sets.

DRAINAGE DESIGN METHOD FOR GRAND VALLEY

In the Grand Valley area, the most important considerations for selecting a drainage design method are the characteristics of an irrigated agriculture in a semi-arid climate. In addition, a special consideration must be made for the artesian conditions produced by the partially confined cobble aquifer discussed by Skogerboe and Walker (1972a). Since the upward movement of groundwater is generally not encountered in the test area, a discussion of drainage when vertical gradients exist will be left until a later section.

Under the conditions noted above, two methods of drainage design seem most applicable: (1) optimum water table and (2) falling water table. In the following paragraphs, the most commonly used techniques in these categories will be discussed.

Optimum Water Table

The optimum water table approach is a steady state solution used throughout the world in humid areas having low intensity and long duration rainfall patterns. The Soil Conservation Service, U.S. Department of Agriculture, has adapted this approach for use in arid and semi-arid regions on irrigated lands by assuming the irrigation to be a uniform recharge event distributed over the irrigation interval.

Most of the initial work on this approach was done by Dr. S.B. Hooghoudt of the Netherlands and is based on the physical model depicted in Figure 8. The model makes the following assumptions:

1. The recharge rate to the water table is constant in time and space;
2. The flow into the drains is equal to the flow reaching the water table (i.e., steady state);
3. The drains are parallel and at the same depth; and
4. The drains perform in a similar manner to open drain ditches in that no flow crosses the tile.

Based on continuity considerations and Darcy's law, the Hooghoudt equation is developed (U.S. Department of Agriculture, 1971),

$$S^2 = \frac{4Kh_m}{w}(h_m + 2d) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

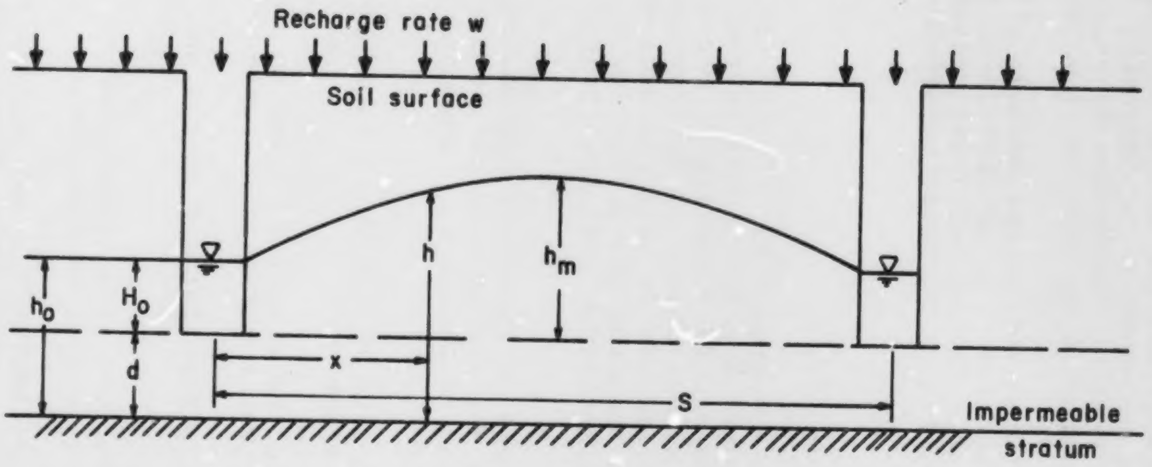

Recharge rate w
Soil surface
h
h_m
h_o
H_o
d
x
S
Impermeable stratum

Figure 8. Model for Hooghoudt's steady state drainage equation (Ayars, 1972).

where S = distance between drains, feet
K = hydraulic conductivity, inches/day
w = uniform recharge rate, inches/day
h_m = height of water table at mid-point between drains, feet
d = saturated depth below the drains, feet.

The first step in using the equation is to select an optimum depth for the water table based on individual crop needs, or by previous experience in the area. A value for the recharge rate is then selected. In humid regions, this can be a drainage coefficient, while in arid regions it would be equal to the deep percolation from an irrigation. Next, the depth to the impermeable boundary is established from subsurface exploration. The saturated depth below the drain (d) is then calculated as being equal to the depth to the barrier minus the depth of drain. The value for the height of the water table at the midpoint of the drains (h_m) is equal to the depth of drain minus the selected depth of the water table. Once a depth of drain is selected, the spacing can be computed and a cost of construction estimated. If the values of d are large, Equation 1 is not valid and a corrected depth, d', is determined from curves prepared by Dr. Hooghoudt (Luthin, 1966).

Falling Water Table

The falling water table, or transient analysis, was developed by engineers of the U.S. Bureau of Reclamation for use in design of irrigation projects in arid and semi-arid areas. This method attempted to incorporate the transient nature of irrigation water and as many of the soil and groundwater conditions as possible. This development was considered necessary because most of the work in drainage prior to this time was accomplished assuming steady state conditions or had been developed to meet the needs of a particular area (Dumm, 1954). The model used in the development is schematically shown in Figure 9. The following conditions are assumed to exist:

1. The total recharge reaching the water table due to irrigation or precipitation is assumed to be instantaneous (i.e., the water table elevation is raised instantly to a new elevation);

2. As flow into the open drainage ditches occurs, the water table descends and drainage from the soil keeps pace with the descent of the water table, assuming that the region above the water table is completely drained; and

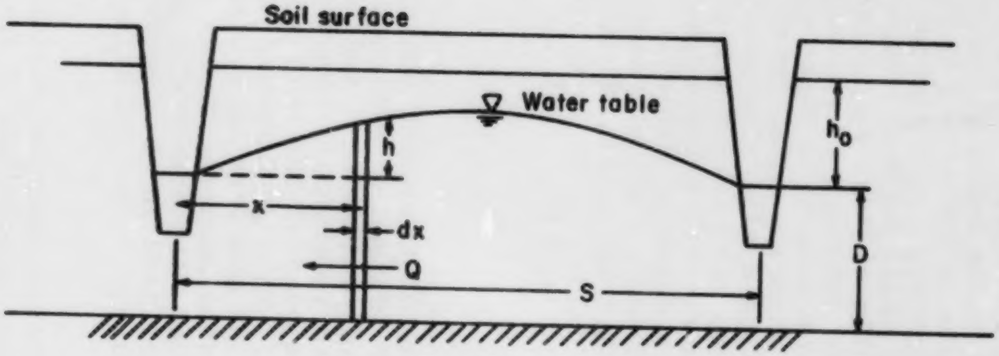

Soil surface
Water table
h_o
h
x
dx
Q
S
D

Figure 9. Model of the transient drainage equation (Ayars, 1972).

3. Flow above the water table is assumed to be zero.

Again, the continuity equation for the model shown in Figure 9 is combined with Darcy's law; and the flow section h + D is assumed to equal some average value D, the equation is given as;

$$\alpha \frac{\partial^2 h}{\partial x^2} = \frac{\partial h}{\partial t} \quad \text{. . . . .} \quad (2)$$

in which,

$$\alpha = \frac{KD}{\phi_d} \ ;$$

where h = height of water table above the drains, feet,
K = hydraulic conductivity, inches/hour,
ϕ_d = specific yield of soil,
t = time, hours,
D = depth of flow below drains, feet
x = distance measured horizontally from the drain, feet.

Solutions to the equation are in the form of a Fourier series, which are dependent on initial and boundary conditions. Solutions which originated in the field of heat transfer have been applied to the groundwater field in equations known as Glover's equation, the transient equation, and also the Bureau of Reclamation equation.

A particular solution of the transient equation is used by the Bureau of Reclamation in conjunction with the concept of "dynamic equilibrium". In using this concept, the elevation of the water table is permitted to fluctuate during the growing season, but the long-term average elevation is fixed. Use of the equation also requires determining the depth to barrier, the hydraulic conductivity and specific yield of the soil, and developing a schedule of recharge events. Having established these factors, the depth of the drains can be varied and the maximum spacing based on deep percolation can be computed. Since this equation is used primarily in arid and semiarid regions, the water table depth is usually assumed to be at least four feet in order to prevent evaporation of groundwater from the soil surface and an accompanying accumulation of salts.

Dumm (1964) reported that Glover originally solved Equation 2 for the case of the drains located above an impermeable barrier by assuming a horizontal water table as the initial condition. In subsequent solutions by Tapp and Moody (Dumm, 1967), the assumption of an initially horizontal water table was not considered an accurate representation, so the water table shape was changed to a fourth order parabola. This solution is currently used by the Bureau of Reclamation. The Fourier series solution of the transient equation for the height of the water table at the midpoint between the drains is:

$$\frac{y_{c,t}}{y_{c,o}} = \frac{192}{\pi^3} \sum_{n=1,3,5,}^{\infty} (-1)^{\frac{n-1}{2}} \frac{n^2 - \frac{8}{\pi^2}}{n^5} \exp\left[- \frac{\pi^2 n^2 \alpha t}{L^2} \right]. \quad (3)$$

where α = diffusivity Kd/s,
K = hydraulic conductivity, inches/hour
d = saturated depth below drain, feet
t = time, hours,
x = distance measured horizontally from the drain, feet
$y_{x,t}$ = height of water table above the drain at distance x and time t, feet
c = midpoint between drains were $x = L/2$, feet.

The initial and boundary conditions used in the solution are:

Initial conditions: $t = 0, 0 \leq x \leq L$

$$y_{x,o} = \frac{8y_{c,o}}{L^4} (L^3x - 3L^2x^2 + 4Lx^3 - 2x^4)$$

Boundary conditions: $t \geq 0$, $x = 0$ or L

$$y_{o,t} = 0 \text{ and } y_{L,t} = 0$$

Consideration must also be given to the physical situation where the drains are located on the impermeable barrier. Solutions to Equation 2 for this condition have been provided independently by Boussinesq and Glover (van Schilfgaarde, 1970). The equation is:

$$L = \sqrt{\frac{9KHt}{2S \frac{H}{Z_c} - 1}} \quad \dots\dots\dots\dots\dots\dots \quad (4)$$

where L = spacing, feet,
K = hydraulic conductivity, inches/ hour
t = drainout period, days
S = specific yield, %
Z = saturated thickness of aquifer at distance x from drains, feet,

c = midpoint between drains, feet,
H = initial saturated depth at midpoint between drains, feet.

The parameters are shown in Figure 10.

The decision to design the drains on or above the barrier depends on the ratio of the saturated depth below the drain to the height of water table above the drain at the midpoint between parallel drains. Dumm (1964) reports that if this ratio is less than 0.10, the drains should be designed on the barrier, and if the ratio is greater than 0.8, the design should use the equation for drains over the barrier. If the ratio falls in the range 0.1 to 0.8, then the best judgment of the designer must be used to select the proper method for solution.

The computations are started by assuming a depth and spacing for the drain and a maximum water table elevation. Using the recharge schedule, the depth of the water table is computed for each recharge and drainout period through the year until the starting point is again reached. If the elevation of the water has returned to the originally assumed elevation, the proper spacing for the given depth has been selected. If this is not the case, a new spacing is selected and the final elevation is then recomputed. Usually, after two trials a straight line interpolation between the computed values of the final water table position will give the correct spacing. The computations are begun with the last irrigation of the season, since this is the time the water table elevation is assumed to be highest. A first estimate of the spacing can be made using the steady state Equation 1 with the value for uniform recharge (w) being equal to the deep percolation losses divided by the minimum recharge interval. A computer program was developed by Ayars (1972) to perform these calculations.

REFINEMENTS IN DRAINAGE DESIGN

In general, the equations used in these drainage designs assume that the water table marks the upper boundary of the saturated zone. This assumption implies that no capillary fringe exists above the water table, that no horizontal flow occurs above the water table, and that the region above the water table is aerated to such an extent that it can provide an acceptable environment for plant growth. The validity of the assumption varies and is primarily dependent on the texture and structure of the soil. For example, a sandy soil would have a small

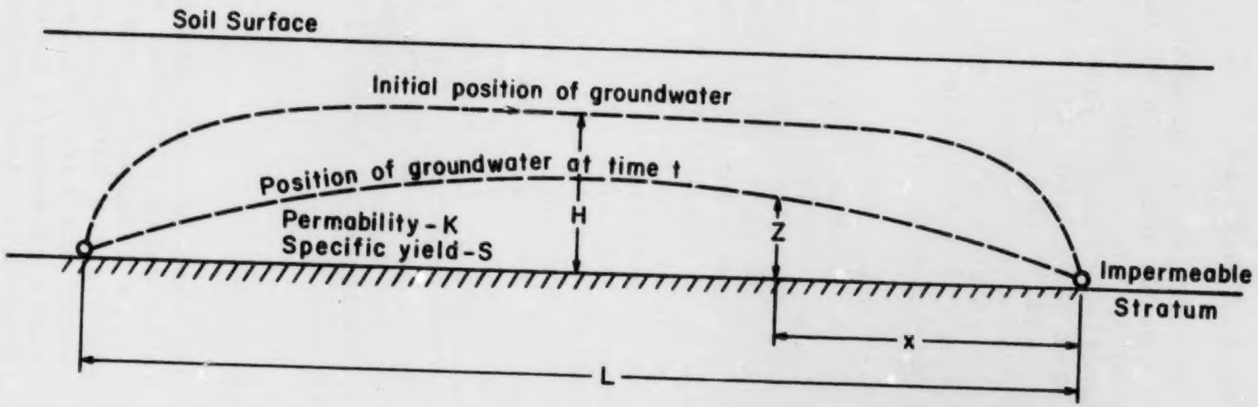

Soil Surface
Initial position of groundwater
Position of groundwater at time t
Permability - K
Specific yield - S
H
Z
Impermeable
Stratum
x
L

Figure 10. Model for transient drainage equation on impermeable barrier.

capillary fringe and the assumption would be fairly good, whereas a fine textured soil with poor structure would have a large capillary fringe and the assumption that the water table marked the upper limit of the saturated zone would be a poor one.

Duke (1972) developed a method using the Dupuit-Forchheimer assumptions in conjunction with the mass continuity equation in the following form:

$$\phi_e \frac{\partial Y_s}{\partial t} = \frac{\partial}{\partial x} \left[K \; Y_k \right] \frac{\partial Y}{\partial x} + Q \quad \dots\dots\dots\dots \quad (5)$$

where ϕ_e = effective porosity as defined by Brooks and Corey (1964),
K = saturated hydraulic conductivity, inches/hour
Y_s = equivalent saturated thickness of aquifer, feet,
Y_k = equivalent permeable thickness of aquifer, feet,
x = horizontal coordinate, feet
t = time, days
Q = volumetric flux rate, cfs.

The variables Y_k and Y_s which account for the effects of capillary flow and storage are defined by the equations,

$$Y_k = Y + H_k \quad \dots\dots\dots\dots\dots\dots \quad (6)$$

$$Y_s = Y + H_s \quad \dots\dots\dots\dots\dots\dots \quad (7)$$

where H_k = equivalent permeable height above the water table, feet,
H_s = equivalent saturated height above the water table, feet,
Y = saturated thickness of the aquifer, feet.

The effective porosity ϕ_e and the variables H_k and H_s are described using the soil property relationships developed by Brooks and Corey (1964), mainly the bubbling pressure, pore-size distribution index, and the residual saturation. Using these same soil property relationships, Duke also defines an elevation (Z_a) above the water table at which the degree of partial saturation permits adequate soil aeration. With application of flow theory in partially saturated and saturated soils, Duke developed the relationships needed to describe flow to drains from above and below the water table.

From this analysis, it was found that the water table fell faster when it was not as in the classical equations. This would mean that the classical equations give spacings that are too narrow. However, when the zone of aeration is considered, the drain spacings have to be reduced in order to maintain the required aerated zone. This means that drain spacings computed using the classical equations are too wide. The effect of the additional height of saturated soil negated the increased rate of water table decline thus requiring spacings narrower than those predicted by the classical theory.

Because the soils in the Grand Valley area have low permeabilities, the adjustments proposed by Duke (1972), will be made on the falling water table approach developed by the Bureau of Reclamation.

FAILURE OF EXISTING SYSTEM

After analyzing methods of drainage design in the previous paragraphs, it is necessary to consider the type of drains which should be used. Excess irrigation water and soils with poor drainage characteristics have been identified in the current study and in previous research as the major cause for high water tables in the Grand Valley. The attempts to alleviate these conditions to date have largely involved open drainage ditches. However, based on an analysis by Kirkham (1960), the system of open drains cannot economically be made effective in releiving the waterlogged condition. Kirkham analyzed the problem of drainage of ponded fields overlying a gravel substratum which is typical of the conditions in Grand Valley. Based on this model, Kirkham concluded:

1. When the depth of the ponded water equals zero, and if the drain spacing is greater than six times the drain depth, the proportion of water entering ditches through the wall will be small compared to that reaching the ditches by underlying gravel;
2. If the depth of the ponded water and the water in the drain each equal zero, then no water will seep through the ditch walls provided the gravel is infinitely permeable compared with the overburden; and
3. When the spacing is greater than six times the drain depth, the influence on drainage will be a function of the height of the water in the ditch.

The conditions in the first conclusion are met immediately following an irrigation, since the drain spacings are considerably greater than six times the drain depths and the depth of ponded water equals zero. This means that for deep percolation to reach the drains it must first travel to the cobble aquifer. The presence of the clay layer in the profile retards this drainage and thus contributes to developing high water tables.

The second conclusion indicates that during the winter when the drainage ditches are empty, seepage is restricted to the cobble aquifer and again the clay layer retards the movement of water. This means that more groundwater can be retained over the winter months, which aids plant growth, but it also means that soil moisture storage capacity is reduced and chances for high water tables are increased.

For the case when the spacing is greater than six times the drain depth, which is the case in the Grand Valley, drainage depends on the height of the water in the ditch. During the irrigation season, the depth of flow is usually one to two feet so it will not be significant in improving drainage.

If open ditch drains were spaced roughly 80 feet apart, based on Kirkham's work, the drainage problem could be solved. However, this would not be economical since most of the cropland would be lost to open ditches. This analysis indicates that reclamation of lands by leaching in the study area must be accomplished by means of drainage other than open drains. In this case, field relief drainage is best suited to the problem of water table control.

SECTION VI

FIELD INVESTIGATIONS

Investigations were conducted during the summer of 1972 to gather data necessary for completing a drainage design for the three farms in the study area and to evaluate the applicability of the results of previous research for use in the study.

Winger and Luthin (1966) as well as Christiansen and Grassi (1969) have suggested a series of investigations necessary to gather all pertinent data needed for a drainage design investigations to be completed:

1. Topographic survey of fields to be drained;
2. Subsurface investigations to determine soil properties and groundwater flow characteristics;
3. Investigate water table movement;
4. Determine sources of excess water;
5. Estimate leaching requirements;
6. Develop irrigation schedules; and
7. Compute groundwater balance.

TOPOGRAPHIC SURVEY

Topographic surveys are necessary for designing tile grade line, computing areas to be drained, identifying tile outlets, and as a base for measuring the slope and fluctuations of the water table. The survey of the three fields to be drained was performed by project personnel using a level and 100-foot tape. Contours were drawn at one-foot elevation intervals and all lateral distances were measured with the tape. The results of the topographic surveys are shown in Figures 11, 12, and 13.

The slope of the fields on the Kelleher and Canaday farms averaged 0.56% in the north-south direction. Contours in each field are uniformly spaced over the length of the field and are parallel across the fields. Surface irrigation with relatively high efficiencies and even distribution should be possible on these fields because of the uniformity of the slope. In contrast to these fields,

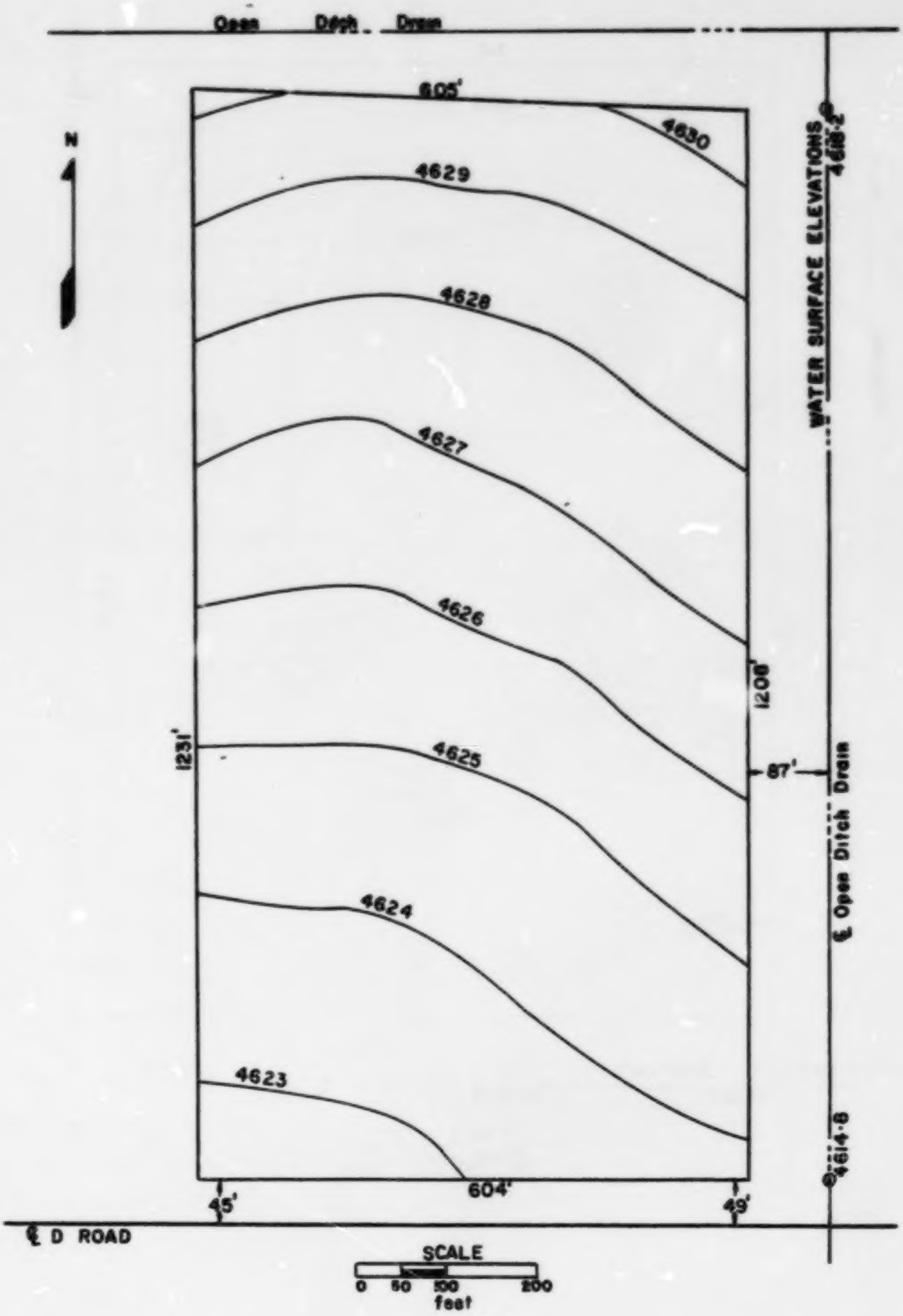

Open Ditch Drain
605'
4630
4629
4628
4627
4626
4625
4624
4623
N
WATER SURFACE ELEVATIONS
4618·2
1208'
1231'
87'
℄ Open Ditch Drain
4614·8
45'
604'
49'
℄ D ROAD
SCALE
0
50
100
200
feet

Figure 11. Topographic map of the Canaday field.

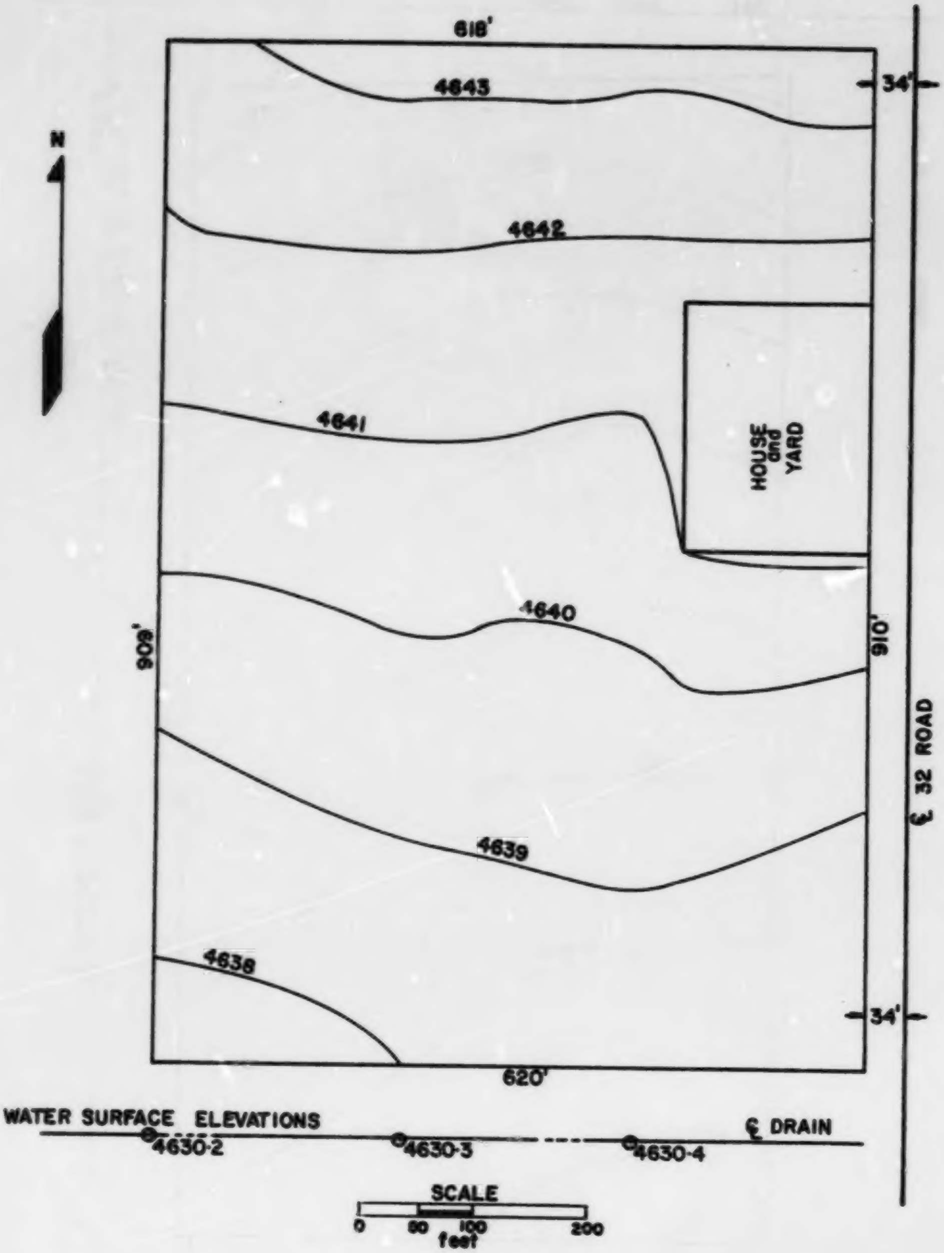

618'
4643
34'
N
4642
HOUSE and YARD
4641
4640
909'
910'
4639
℄ 32 ROAD
4638
34'
620'
WATER SURFACE ELEVATIONS
℄ DRAIN
4630·2
4630·3
4630·4
SCALE
0
50
100
200
feet

Figure 12. Topographic map of the Kelleher field.

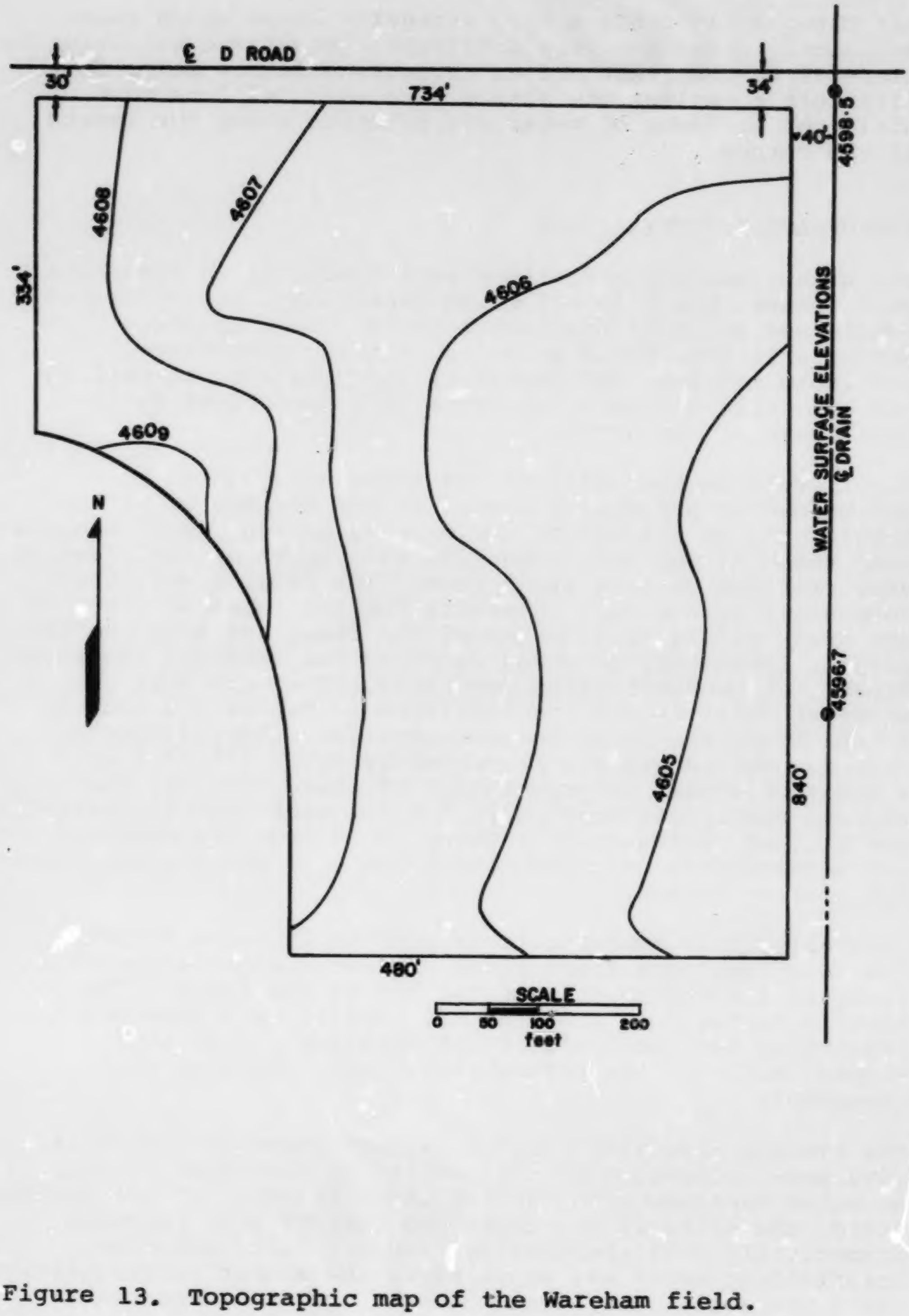

℄ D ROAD
30'
734'
34'
40'
4598.5
334'
4608
4607
4606
4609
4605
N
WATER SURFACE ELEVATIONS
℄ DRAIN
4596.7
840'
480'
SCALE
0
50
100
200
feet

Figure 13. Topographic map of the Wareham field.

the Wareham field has a very irregular shape which makes efficient irrigation very difficult. The large variation in slope along the length of an irrigation furrow makes it difficult to select the stream size which will be most efficient in terms of water distribution along the length of the furrow.

SUBSURFACE INVESTIGATIONS

The subsurface investigations were conducted to determine soil groups, their location and continuity, salt-affected soils, and areas of high water table. Soil moisture characteristics, field capacity, wilting percentage, available moisture and capillary distribution, as well as the hydraulic conductivity, were also determined during this phase of the study.

Salt levels in the soils of the three study farms were determined by project personnel at the beginning, in the middle, and at the end of the growing season. Soil samples were taken at one-foot intervals to a depth of four feet at nine stations on each study farm. The samples were then composited by one-foot intervals for the three stations at the head, middle, and bottom of the field and taken to the project laboratory in Grand Junction for chemical analyses. Electrical conductivities were measured on the soil moisture extracts and are tabulated in Tables 3,4, and 5. In addition, the ionic constituents for selected samples were determined and are presented by Ayars (1972). As a means of visual interpretation of these results, the average electrical conductivities for each sampling period are plotted in Figure 14. These plots show the movement and accumulation of salts within the soil profile throughout the growing season.

Generally, salt concentrations tend to increase towards the lower end of a field since a greater application of irrigation water is made at the top of the field. The data in Tables 3,4, and 5 do not confirm this hypothesis, indicating the local effects of relatively flat land slopes, soils of low permeability, and irregular field topography.

The average electrical conductivities shown in Figure 14 give some indication of the quality of the land, as well as water management on each of these fields. On the Canaday field, the salts in the upper two feet of soil increase dramatically over the growing season. This indicates insufficient water was supplied in the summer to adequately leach the soil. The levels of salt are still acceptable

Table 3. ELECTRICAL CONDUCTIVITY VALUES FOR SOILS ON THE CANADAY FIELD.

Electrical Conductivity of Composite Samples By Field Location (μmhos/cm).

Date of Sampling	Depth of Sample (feet)	Location North End	Middle	South End	Average
6/23/72	0-1	1635	2005	1741	1794
	1-2	6647	2638	1159	3481
	2-3	4220	4861	1504	4745
	3-4	4590	5899	4115	4868
7/26/72	0-1	1444	2167	1648	1753
	1-2	4540	2112	1135	2596
	2-3	4275	5072	4731	4693
	3-4	4650	5684	6077	5470
10/ 5/72	0-1	6280	4885	2425	4530
	1-2	5787	7495	2005	5095
	2-3	5036	6397	5994	5809
	3-4	4540	7337	5945	5941

Table 4. ELECTRICAL CONDUCTIVITY VALUES FOR SOILS ON THE KELLEHER FIELD.

Electrical Conductivity of Composite Samples By Field Location (μmhos/cm).

Date of Sampling	Depth of Sample (feet)	Location			
		North End	Middle	South End	Average
6/28/72	0-1	1782	1635	1637	1685
	1-2	1175	1226	1637	1346
	2-3	1120	1073	7164	3119
	3-4	6959	7164	6571	6898
7/24/72	0-1	2884	1498	2218	2200
	1-2	1602	1139	1346	1362
	2-3	3817	954	5365	3379
	3-4	3726	3090	3405	3407
10/ 5/72	0-1	2090	2315	3043	2483
	1-2	1072	1229	1259	1187
	2-3	4723	1194	7402	4440
	3-4	6178	966	7184	4776

Table 5. ELECTRICAL CONDUCTIVITY VALUES FOR SOILS ON THE WAREHAM FIELD.

Electrical Conductivity of Composite Samples
By Field Location (μmhos/cm).

Date of Sampling	Depth of Sample (feet)	Location			
		West Side	Middle	East Side	Average
7/ 6/72	0-1	1595	5195	3079	3289
	1-2	3769	13379	11166	9438
	2-3	6158	15266	11680	11035
	3-4	4884	15927	12741	11184
8/11/72	0-1	3869	7878	4354	5367
	1-2	7004	13456	11197	10552
	2-3	4865	15316	11386	10522
	3-4	4495	16793	12835	11374
10/ 5/72	0-1		No Data		
	1-2				
	2-3				
	3-4				

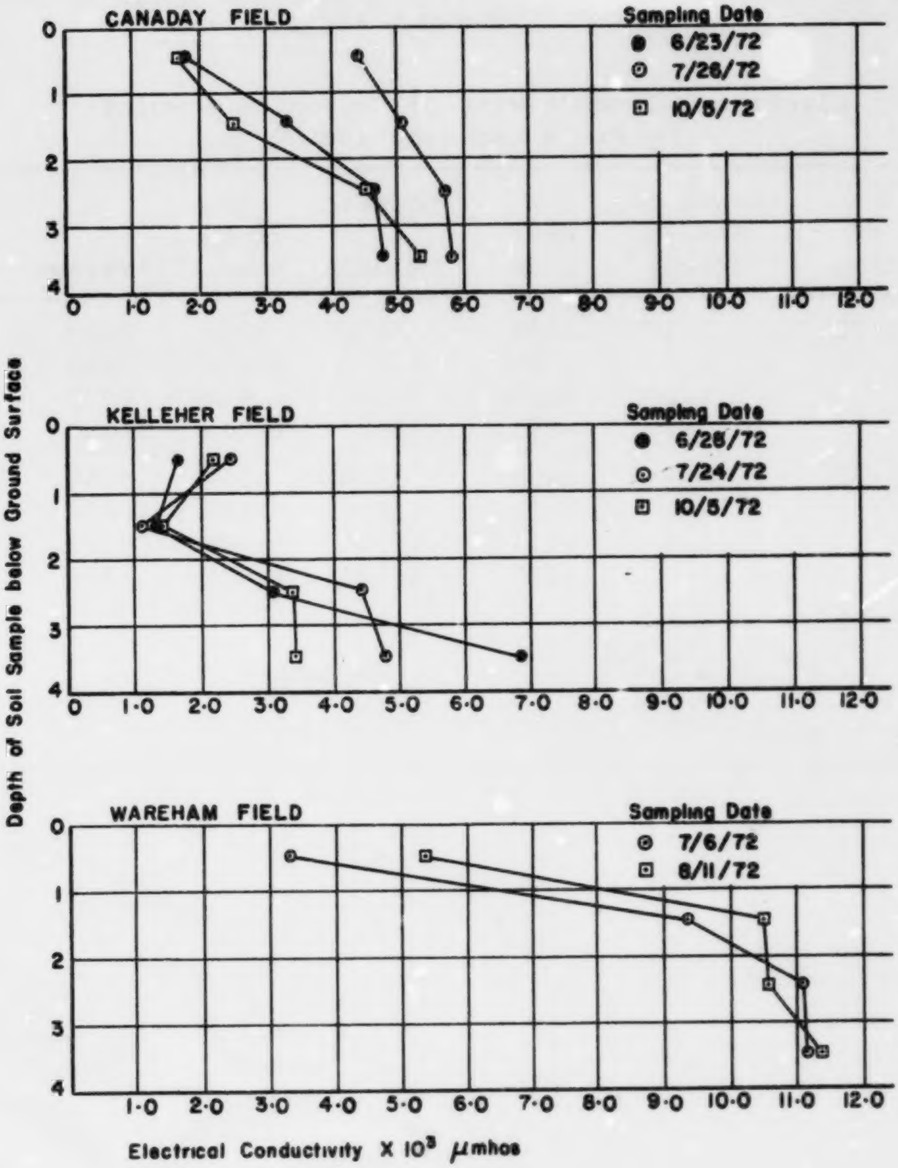


Figure 14. Relationship of the average soil electrical conductivity to depth in the soil profile on the study fields for 1972.

in that they will not restrict plant growth at the present time, but this field should be carefully managed to prevent further buildup of salts.

The soil on the Kelleher field is relatively free of salts and was maintained that way throughout the 1972 growing season. The first irrigation was quite effective in leaching the salts from the four-foot depth of the root zone. After the first irrigation, there was some increase in salts, but these can easily be leached and will not be a problem for future productivity of the field.

The soil on the Wareham farm is already high in salts below a depth of one foot. Figure 14 shows that the salts increased during the summer, indicating insufficient water being applied for leaching. Consequently, this field requires a more salt-tolerant crop and more careful application of irrigation water.

Mechanical analysis to determine soil texture, as well as pressure plate tests to estimate soil moisture values at saturation, field capacity and wilting point, for the soils in the study fields were conducted in the Soils Laboratory at Colorado State University. The results of these laboratory analyses are presented in Table 6. The soils were generally clays and silty clays containing very little sand. The total available water (the water available to plants for growth) was computed to be 2.4 inches per foot of soil based on the soil moisture and soil moisture tension data between 1/3 and 15 bars given in Table 6.

Hydraulic conductivity was estimated using the single-auger-hole method discussed by Luthin (1966). This method was considered the most practical technique because of the simplicity of data collection and the ease of computation. The auger-hole method has the additional advantages of using soil water for the measurement, using a large sample, and reflecting the horizontal component of conductivity.

The method used for determining hydraulic conductivities from auger-hole data in which an impermeable boundary is at a great depth is shown in Figure 15 (Maasland and Haskew, 1957). The assumptions used in this development are:

1. The water table is not lowered in the region around the auger hole when the hole is pumped at the beginning of the test;

Table 6. TEXTURAL CLASSIFICATION AND MOISTURE HOLDING CAPACITY OF THE SOILS ON THE STUDY FIELDS.

Farm	Sampling Location in Field	Sand (%)	Silt (%)	Clay (%)	Texture	Percent Moisture by Weight for Given Pressures				
						0 Bar	1/3 Bar	1 Bar	10 Bar	15 Bar
Canaday	SE Corner	3	56	41	SiC	40.0	26.8	18.4	12.7	13.3
	SW Corner	9	47	44	SiC	43.4	27.6	18.8	14.0	13.2
		9*	48*	43*	SiC*					
	Top	15	41	44	SiC	42.2	24.4	16.8	12.9	13.2
Wareham	NE Corner		50	50	C	52.5	29.5	21.3	16.6	15.1
			48*	52*	C*					
	SE Corner		39	61	C	49.4	30.6	23.1	18.0	17.3
			39*	61*	C*					
	Top		46	54	C	45.8	28.8	21.2	16.3	15.4
			44*	56*	C*					
Kelleher	Top		57	43	C	44.4	25.5	18.5	14.0	13.4
			56*	44*	C*					
	SE Corner		57	43	C	45.1	26.0	18.9	13.8	13.4
			54*	46*	C*					
	SW Corner		54	46	C	44.0	30.0	19.7	14.2	13.4

*Duplicate Values

Texture Codes - SiCL: Silty Clay Loam
SiC : Silty Clay
C : Clay
CL : Clay Loam
L : Loam

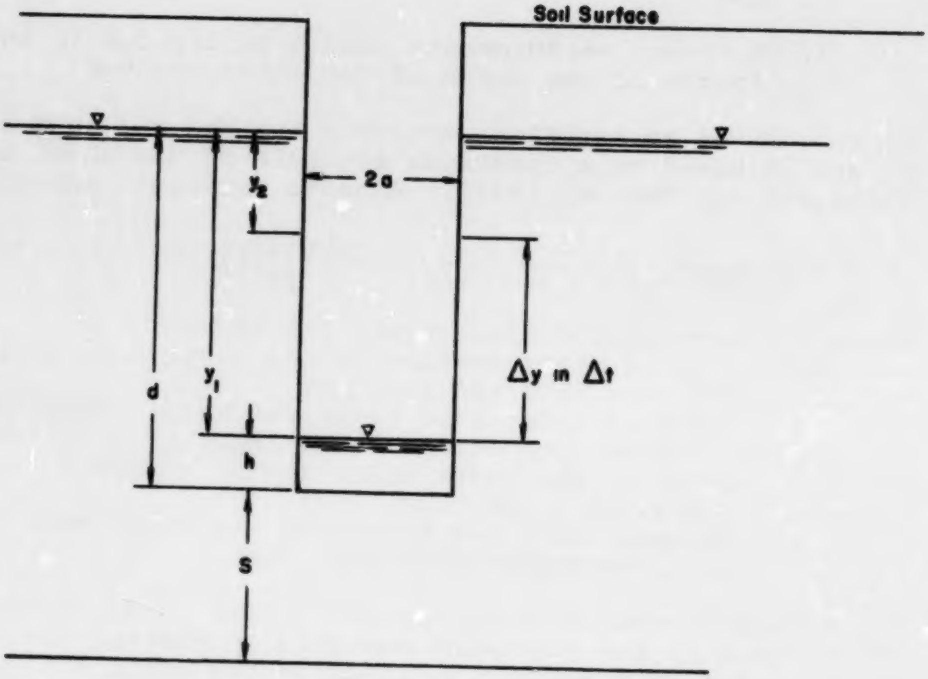

Soil Surface
y_2
2a
d
y_1
Δy in Δt
h
S

Figure 15. Geometry of single-auger-hole method used in homogeneous soil (Ayars, 1972).

2. Flow into the auger hole is assumed to be lateral; and

3. Recovery measurements should be limited to one-fourth of the depth of the water removed.

Ernst derived an empirical equation for the case shown in Figure 15 based on a numerical analysis of the exact solution (Maasland and Haskew, 1957). Ernst's empirical equation is:

$$K = \frac{4000}{(20 + d/a)\ (2 - y/d)} = \left[\frac{a}{y}\right]\left[\frac{\Delta y}{\Delta t}\right] \cdot \cdot \cdot \cdot \cdot \cdot \cdot \quad (8)$$

where K = hydraulic conductivity, inches/hour
Δy = rise of water surface in the auger hole during the time interval Δt, feet,
d = depth of auger hole below the water table, feet,
y = distance from static water table to elevation of water in the auger hole, feet
a = radius of auger hole, feet
s = distance from the bottom of the auger hole to the impermeable boundary, feet.

The values of hydraulic conductivity have an accuracy of ±20 percent if the following conditions relating the size of the auger hole and the position of the water table (with lengths in centimeters) are met:

$$3 < a < 7,\ 20 < d < 200,\ y/d > 0.2,\ s > d$$

where the parameters are as given in Figure 15.

Data used in calculating hydraulic conductivities including depth of hole, depth to water surface at equilibrium, and rate of rise of water in the auger hole after the water had been pumped down to a new elevation were collected by project personnel. The collected data were recorded and hydraulic conductivities computed on a form used by the United States Buraeu of Reclamation (USBR).

Once the data were transferred to the USBR form, the computations were straightforward. The data for the recovery rate are plotted as shown on Figure 16 from which the value for the total depth of drawdown (y_o) is estimated. Then, a value for $0.8y_o$ is calculated and plotted on the graph. The values for y_o and $0.8y_o$ are then averaged to give a mean y. After computing the ratios of mean depth to water table divided by the radius of auger hole and initial depth of water table divided by the radius of auger hole, the solution diagram of Maasland and Haskew (1957) which employs these ratios can be used. The solution diagram selected for use depends on whether the auger hole terminates

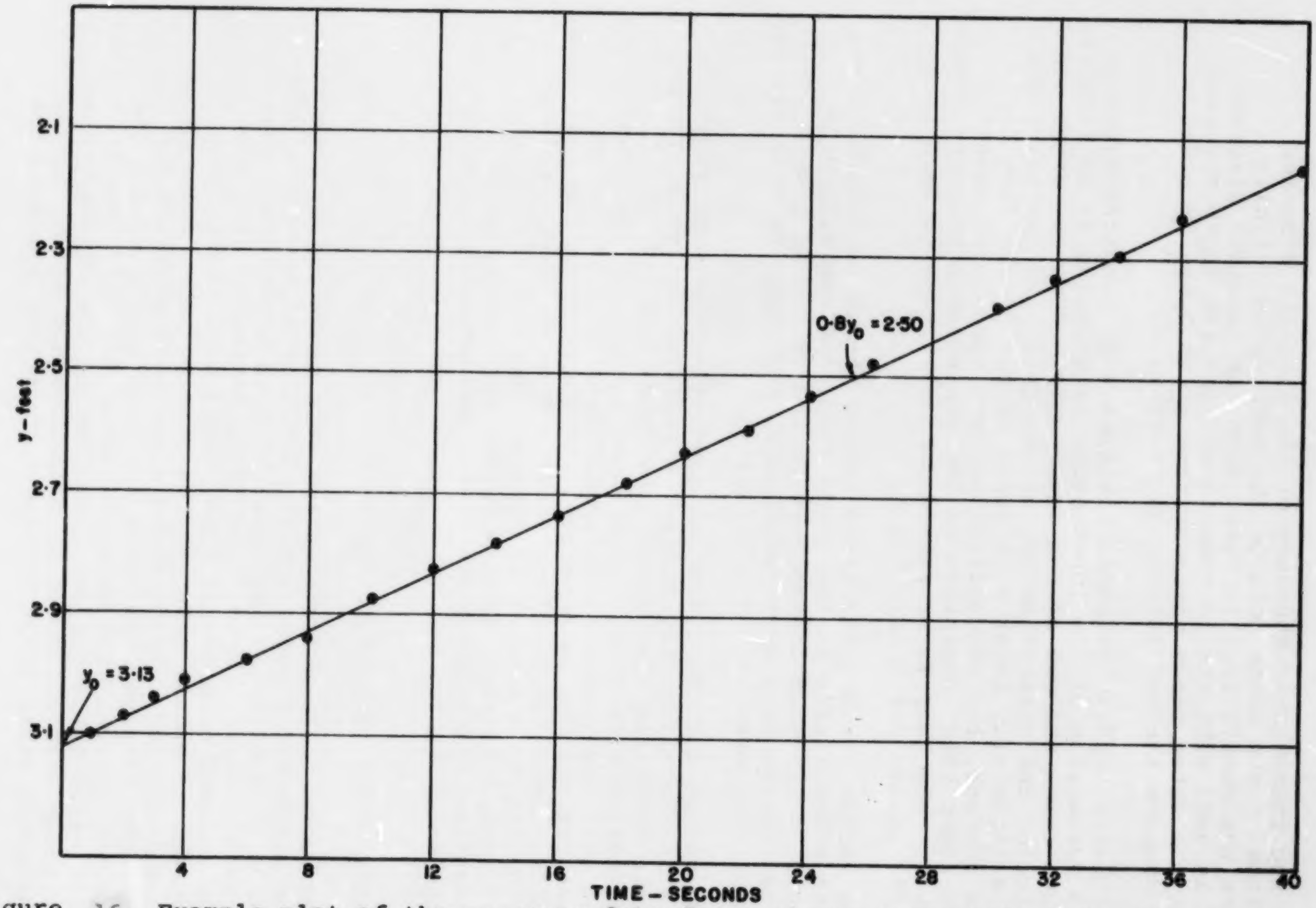


Figure 16. Example plot of the recovery data for a single auger hole hydraulic conductivity test.

on the impermeable boundary or the distance from the bottom of the auger hole to the barrier is infinite. Once the coefficient is taken from the solution diagrams, it is used with the increments of time and depth computed for the water table movement from y_o to $0.8y_o$ in order to compute the hydraulic conductivity.

Initially, hydraulic conductivities were computed based on the assumption of the impermeable layer being at an infinite depth below the end of the auger hole. However, after considering the stratification of the soil, and the existence of a tight clay layer at a depth of six to ten feet below the surface, the conductivities were recomputed assuming the auger hole terminated on the impermeable boundary. Tests run in this clay layer showed conductivities of less than 0.043 inches per hour.

The values for all the tests run on the three fields, along with other fields in the study area, are summarized in Table 7. In each instance where the values of hydraulic conductivity have been recomputed, the auger hole terminated on or very near to the clay layer.

The values for the hydraulic conductivities were very low in the silty clay soils. A textural analysis of the soils indicated they were quite dense and had very little aggregated structure. With these conditions and considering the soil type, conductivities of less than one to two feet per day can be expected. In contrast to the silty clay soils, tests run on river sands and sandy loams produced conductivity values of 53 feet per day and 13 feet per day, respectively. Some problems were encountered in measuring hydraulic conductivity because of the lack of a high water table.

WATER TABLE INVESTIGATIONS

The water table investigations were conducted to determine the slope and fluctuation in elevation of the water table, along with establishing areas of high water table over the growing season. From these data, estimates were made of the natural groundwater flow, along with identifying sources of excess water at the grid point. Access tubes were installed in each field where soil moisture and salinity samples were taken and read weekly during the growing season. The data collected for 1972 show that a high water table did not exist during the growing season, although data collected by Skogerboe and Walker (1972b) indicated water table problems in earlier years in the

Table 7. HYDRAULIC CONDUCTIVITY DATA FOR SOME FIELDS IN THE GRAND VALLEY SALINITY CONTROL DEMONSTRATION PROJECT.

Test No.	Farm		Depth of Test (ft)	Hydraulic Conductivity S=∞	S=0	Soil Type at Test Depth
1	Bulla	1	2.7 - 9.8	1.70	1.89	Lt. bn silty clay loam, moderately dense & compact
		2		0.98	1.10	
2	Kelleher	1	2.9 - 8.3	0.76	0.85	Lt. bn gray heavy silty clay, massive
		2		0.49	0.68	
3	Canaday	1	6.0 - 9.8	53.30	N/A	River sand-gravel
		2		45.80	N/A	
4	Martin		8.5 -11.3	1.33	1.50	Massive lt. bn gray silty clay loam
5	No test					
6	Kelleher	1A	5.7 - 8.7	0.47	0.67	Lt. bn gray silty clay dense, massive
		2A		0.45	0.53	
		1B	5.9 -10.1	0.25	0.30	Heavy silty clay dense, massive
		2B		0.25	0.37	
7	Wareham	1	6.4 - 9.2	0.36	0.60	No data
		2		0.33	0.55	
8	Kelleher	1	9.0 -11.9	1.57	1.89	Med gray silty clay dense massive to gray bn heavy loam
		2		1.49	1.71	
9	Canaday	1	5.8 -11.0	0.068	0.086	Lt. bn gray silty clay loam, dense to Bn gray silty clay loam dense & compact, massive
		2		0.074	0.084	
10	Canaday	1	6.9 -11.0	0.038	0.046	Brown gray silty clay massive, dense, compact
11	Bulla	1	6.6 -10.9	0.46	0.55	Brown-gray heavy loam, silty clay loam massive moderately compact
		2		0.46	0.57	
12	Wareham	1	7.3 -10.7	13.8	N/A	Brown loam to reddish brown fine sandy loam
		2		14.8	N/A	

locality of those farms. A definite answer cannot be readily given to explain the low water table during this year. Much lower groundwater levels were also found on other farms being studied in this area on which measurements have been made for three years. It is believed that the low winter moisture for the past year, which was the lowest precipitation measured during 82 years of record, effectively reduced the soil permeability due to a lack of mechanical structuring of the soil as it alternately freezes and thaws. Therefore, less water moved into the soil both during the winter because of low precipitation and during summer because of reduced soil permeability. Thus, water tables were generally lower during the 1972 irrigation season.

SOURCES OF EXCESS WATER

An important aspect of drainage studies and subsequent tile drainage designs is evaluating the sources of the water causing the waterlogging conditions. In most instances, deep percolation from irrigation or precipitation, seepage from canals, movement of water from adjacent areas, and artesian water are the major sources of excess water. Data collected during the water table investigations indicate that each of these possibilities exist in the test area.

The net irrigation on the field (infiltration into the soil root zone) was calculated from inflow-outflow data collected by continuous stage recorders mounted on flumes installed in the head and tailwater ditches of each field. Deep percolation from irrigation was determined by measuring the net inflow to the field and subtracting the estimated consumptive use for the plants and the change in root zone soil moisture.

Data on the slope of the water table, the height of the water in a field and the thickness of the aquifer, which were taken in previous investigations, can be used to estimate the natural groundwater flow and its source. The slope of the water table and area of the flow section are the data needed to compute the volume of groundwater flow using Darcy's law, as given in the following form:

$$Q = K D L i \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

where Q = total flow, cfs,
K = hydraulic conductivity, feet/sec,
D = permeable depth, feet,
L = width of flow boundary, feet
i = slope of water table.

The groundwater contribution to the drainage system from adjacent areas can also be estimated using this equation.

The volume of water from artesian sources is dependent on the hydraulic head in the aquifer and the thickness and hydraulic conductivity of the overlying materials. Piezometers extending to various depths in the soil profile, as well as the cobble aquifer, were used to determine the general gradients in the study area. Data reported by Skogerboe and Walker (1972b) show the average vertical gradients to be downward in the study area. It was the experience of the investigators that when the cobble aquifer was penetrated by an auger hole, water would immediately be present, but its elevation was less than the equilibrium elevation in the hole, thus also indicating a downward vertical gradient towards the aquifer.

Of the sources discussed, only deep percolation from irrigation is considered significant in this study. Seepage from canals has been eliminated because none of the fields are bounded by a canal. Since the area is semi-arid, with the majority of rains occurring in the summer being less than 0.1 of an inch, deep percolation from precipitation is not significant. The existence of downward gradients to the aquifer and the relative impermeability of the clay layer over the aquifer eliminate the artesian source from further consideration.

Groundwater flow into the fields is difficult to estimate. However, two of the fields in the study are bounded on two sides by 12-foot deep drainage ditches, one being bounded on the north and east and the other on the east and south. The third field has a 12-foot ditch at its south end. It is assumed, therefore, that groundwater flow from adjacent areas into the three fields is not significant because the ditches act as barriers to flow through the field.

LEACHING REQUIREMENT

For irrigated agriculture in arid and semi-arid areas, the maintenance of a salt balance in the root zone is essential for continued productivity. To achieve this balance, water in excess of the consumptive needs of the crop must pass through the root zone. The United States Salinity Laboratory has defined the leaching requirement as the fraction of irrigation water which must be used to control salinity, and which can be mathematically expressed as (U.S. Department of Agriculture, 1954);

$$LR = \frac{D_{dw}}{D_{iw}} = \frac{EC_{iw}}{EC_{dw}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (10)$$

where D = depth of water, inches,
D_{dw} = depth of drainage water, inches,
D_{iw} = depth of irrigation water, inches,
EC = electrical conductivity in μmhos/cm,
LR = leaching requirement expressed as a fraction

Alternately, the depths of drainage can be expressed as a function of the consumptive use requirement of the plant, D_{cw}:

$$D_{dw} = \frac{EC_{iw}}{EC_{dw} - EC_{iw}} D_{cw} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (11)$$

The leaching requirement concept assumes a long-term average of salt concentration levels, a uniform water application, no precipitation of soluble salts in the soil, and no salt uptake by the crop.

IRRIGATION SCHEDULES

Irrigation schedules are required for each crop grown on a field in order to estimate the deep percolation from irrigation of each crop, along with determining which crop will be the limiting case. The elements required to construct a schedule include the length of the irrigation season, effective rainfall, snowmelt, total readily available water, and estimates of the daily consumptive use.

The first elements are easily obtained since the irrigation season is fixed by the irrigation company and climatological data from the U.S. Weather Bureau is available to estimate the effective depths of snow and rain.

Estimating consumptive use requires selecting an evapotranspiration equation which is suitable for use in the area and is compatible with available data. The Blaney-Criddle formula, as modified by the Soil Conservation Service, and the Jensen-Haise formula were compared on estimated total consumptive use and daily consumptive use in relation to consumptive use values computed by the U.S. Bureau of Reclamation's irrigation scheduling program in the Grand Valley. Although the Jensen-Haise method estimated consumptive use values somewhat higher than the other two, it was selected because it would provide a factor of safety in the drainage design (which is true when farm deliveries are properly managed, such as by irrigation scheduling).

The Jensen-Haise equations are:

$$E_{ta} = C_T(T - T_x)R_s \quad . . . . \quad (12)$$

$$C_T = \frac{1}{C_1 + C_2C_H} \quad . . . . \quad (13)$$

$$C_H = \frac{50 \text{ mb}}{(e_2 - e_1)} \quad . . . . \quad (14)$$

$$C_2 = 13°F \quad . . . . \quad (15)$$

$$C_1 = 68°F - (3.6°F \text{ elev}/1000) \quad . . . . \quad (16)$$

$$T_x = 27.5°F - 0.25\ (e_2 - e_1)°F/\text{mb} - (\text{elev}/1000) \quad (17)$$

where e_2 = saturation vapor pressure of the mean maximum temperature for the warmest month, millibars,
T = mean monthly temperature, °F,
R_s = average daily solar radiation, langleys,
E_{ta} = evapotranspiration of well-watered alfalfa, langleys (langleys x 0.000673 = inches).

Once the constants for the area have been established, use of the equation requires only the mean daily temperature, the average daily solar radiation for the month, and a crop coefficient which gives the actual plant consumptive use as a function of the plant growth stage.

The data and the method used in computing an irrigation schedule for corn are shown in Table 8. The allowable depletion was computed based on a four-foot root zone and a 50-percent depletion of the totally available water. The crop coefficients were given as a function of the percentage of the growth until full crop cover. In this case, the interval used to change coefficients was eight days.

The date of irrigation will be specified as the date when the readily available water in the soil has been depleted as computed by summing the daily consumptive use values. The daily use value is equal to the monthly estimated evapotranspiration (which has the units of inches per day) multiplied by the crop coefficient.

Once the dates for the irrigation have been established they are combined with natural recharge events to provide the recharge event schedule needed for the spacing computation, as shown in Table 9. The proposed irrigation schedules used in this study are given by Ayars (1972).

Table 8. EXAMPLE CALCULATION OF IRRIGATION SCHEDULE FOR CORN USING THE JENSEN-HAISE METHOD.

Interval	Et_p (in/day)	Crop Coefficient	Daily use (in/day)	Depletion in Interval (inches)	Date of Irrigation
April 15					April 15
May					
15-23	.276	0.20	.0552	0.44	
24-31		0.23	.0635	0.44	
June					
1	.372	0.23		0.09	
2-10		0.29	.1080	0.86	
11-19		0.38		1.13	
20-28		0.49	.1820	1.46	
29-30		0.61	.2270	0.45	June 30
July					
1-6	.402	0.61	.2450	1.47	
7-15		0.72	.2890	2.32	
16-19		0.82	.3290	1.31	July 19
19-23				1.31	
24-31		0.91	.3660	2.92	
August					
1-2	.342	0,96	.3280	0.65	August 2
2-8			.3280	1.97	
9-18		0.99	.3380	3.38	August 18
19-28		0.99	.3380	3.38	
29-30		0.93	.3380	0.68	
September					
1-4	.256	0.93	.2380	0.95	September 4
4-8				0.95	
8-18		0.82	.2100	2.10	
				28.25	

Assumptions:

1. allowable soil moisture depletion = 4.9 inches
2. preirrigated to fill root zone on April 15
3. crop planted May 15
4. 85 days to full crop coverage of soil surface

Table 9. EXAMPLE OF PROPOSED YEARLY RECHARGE SCHEDULE USED FOR DRAIN SPACING BASED ON AN IRRIGATION SCHEDULE FOR CORN.

Recharge Source	Date of Recharge	Interval Between Recharge (Day)	Depth of Irrigation (inches)
I	Sept 4		0
		112	
B	Dec 25		0
		111	
I	April 15		4.9
		76	
I	June 30		4.9
		19	
I	July 19		4.9
		15	
I	Aug 2		4.9
		16	
I	Aug 18		4.9
		17	
I	Sept 4		4.9
		112	
B	Dec 25		

I = Irrigation

B = Between Irrigations

GROUNDWATER BALANCE

Data from each of the previous investigations are compiled at this point in the form of an equation to estimate the volume of groundwater to be removed by natural or artificial drainage methods to achieve dynamic equilibrium. Christiansen and Grassi (1969) give the following mass balance equation for determining drainage requirements:

$$IR + CS + P \pm GW_{io} + GW_a - ET_c - ET_n - GW_d - DR = \pm \Delta GWS \quad (18)$$

where IR = contribution to the groundwater from water applied by irrigation, acre-feet

CS = canal seepage losses reaching the groundwater, acre-feet;

P = precipitation reaching groundwater, acre-feet;

GW_{io} = net groundwater inflow directly from, or outflow to the adjacent area, where a plus sign indicates a groundwater accretion, acre-feet;

GW_a = groundwater inflow from artesian aquifers, acre-feet

ET_c = the evapotranspiration by agricultural crops from groundwater, acre-feet

GW_d = downward drainage to pumped aquifers, acre-feet;

DR = outflow from the drainage system, acre-feet;

ΔGWS = change in groundwater storage where a plus sign indicates groundwater accretion and a rise in the water table, acre-feet.

When the system has achieved dynamic equilibrium for a season, $\Delta GWS = 0$. In this application of drainage technology to field drainage in the Grand Valley, Equation 18 reduces to:

$$IR - ET_c = \Delta GWS \quad (19)$$

SECTION VII

DESIGN, CONSTRUCTION AND EVALUATION OF FARM DRAINAGE

GENERAL DESIGN FACTORS

The investigations reported in the previous section indicated that the primary parameters in field drainage design in the Grand Valley are deep percolation, evapotranspiration by crops, and groundwater storage changes. Deep percolation depends on many factors describing the condition of the soil, uptake rate by the crops, and irrigation practices.

The relationships between the water and salt flows within the confines of a farm (inflows, precipitation, field tailwater, deep percolation, evapotranspiration, soil moisture storage changes, etc.) have been traditionally described by an efficiency value. For example, irrigation, farm, field, application, and water use efficiencies are commonly used, but often not consistantly. Even in the exhaustive treatment of the various measures of irrigation efficiency given by the American Society of Agronomy in its Monograph No. 11, there are discrepancies among the contributing authors. A worthwhile statement is made in Chapter 61, p. 1120, pointing out the disparity in use of such terms and noting that no standards have been accepted (Hagen, Haise, and Edminster, 1967).

In the evaluation of on-farm improvements designed as salinity control measures, an absolute necessity exists for delineating the effects of field tailwater and deep percolation. On page 776 of the Agronomy Monograph No. 11, irrigation, farm and field efficiencies are distinctive depending on the point of measurement in the irrigation system. The work reported in this writing and similar work by Skogerboe and Walker (1972a) and Skogerboe, Walker, Taylor, and Bennett (1974) has encompassed only the farm boundaries. The measure of irrigation efficiency therefore selected and denoted "farm efficiency" evaluated the percent of water supplied to the farm or farms which was consumptively used by the crops. It should be noted that inefficiencies result when insufficient water is not made available to the plants because of field tailwater or deep percolation. To delineate the effects of deep percolation, a measure defined as "application efficiency" which is congruent with uses in the Agronomy Monograph No. 11 on pages 877, 878, 894, 1121, and 1122 was used. Application efficiency thus defined is the percentage of water applied to the soil which is consumptively used by the crops. In this case, inefficiency results only from deep percolation losses (Hagen, Haise, and Edminster, 1967).

A series of curves using the irrigation schedule for each of the major field crops grown in Grand Valley was developed, which related the leaching requirement to the drain spacings for the physical conditions found in each study field. An analysis to determine whether the maximum spacing could be achieved in these fields by designing the drains above the barrier or on the barrier indicated that the drains designed on the barrier will have the maximum spacing. Consequently, the curves of drain spacings versus leaching requirement were developed for drains placed on the barrier. The values for hydraulic conductivity and depth to barrier for each field used in the analysis were determined based on experience in the field, coupled with the data presented in Tables 9 (example) and 10. The values for the specific yield were taken from Dumm (1967). These spacing design curves are presented as Figures 17, 18, and 19.

SELECTION OF CONSTRUCTION SITES

In evaluating the irrigation and drainage needs on each of the three farms, it became apparent that the only field needing drainage was the Wareham farm (Ayars, 1972). Both the Kelleher farm and the Canaday farms were relatively well managed and could thus prevent high water tables by increasing the efficiency of early irrigations. Since the drainage investigation results for these two latter fields are reported by Ayars (1972), the results relevant to the Wareham field will be emphasized herein.

Field Description

The Wareham field contained 11.6 acres of alfalfa and weeds being used as a pasture. The field was pastured continuously even during irrigation, resulting in the soil surface being highly compacted. The soils are silty clays, silty clay loams, and clays, which are generally dense and massive, having very poor structure and low values for hydraulic conductivities. The salt content is very high with the electrical conductivity averaging over 9 mmhos/cm through the soil profile. Figure 14 shows that the salt content increases over the growing season, implying that the irrigation water was ineffective in leaching the soil.

Water management on this field was extremely poor during the study period as shown by the efficiency data in Table 11. The presence of livestock during irrigation periods contributed to this efficiency by destroying the furrows used for irrigation.

Table 10. TEXTURAL ANALYSIS OF THE SOIL PROFILES OF THE AUGER HOLES USED FOR HYDRAULIC CONDUCTIVITY TESTS ON THE STUDY FIELD

Farm	Canaday				Kelleher		Wareham	
Location in Field	South end of Field	NW Corner	Center	SE Corner	NE Corner	SW Side	SW Corner	North Center
1 -	Light Gray silty clay massive dense compact	Silty Clay Loam	Silty Clay Loam	Light Gray heavy Si Cl Loam, massive, dense compact	Lt Gr Brn SiCl Loam Mod Granular	Lt Gr Brn Silt Loam to Silt Cl Loam	Gr Brn Si Cl Loam	Silty Clay
2 -		Loam Silty Clay Loam					Gr SiCl Loam Granular	Silty Clay Loam
3 -					Light Brn Gray, Si Clay Loam moderately dense massive		Lt Gr Silt Clay moderately dense, massive	Silty Clay
4 -		Loam to Silt Loam	Silt Loam			Brown Gray Light Silty Clay moderately compact massive		
5 -			Silty Clay Loam	Light Brown Gr Silt Clay Loam Massive, Unstable When Saturated			Brn loam to light clay loam	
6 -		Brn Gr Si Clay Loam						
7 -		SiltLoam massive	Silty Clay		Medium Gray lt. silty cl dense, massive, sticky		Lt brn loamy sand unstable	
8 -							Brn fine sand loam	Silty Clay Loam
9 -	Brown Sandy Loam	Silty Clay Loam dense compact				Brn Gr heavy Si Cl dense massive		Brown fine sandy loam
10 -					Brown to Gray Brn heavy loam massive			
11 -								
12 -								

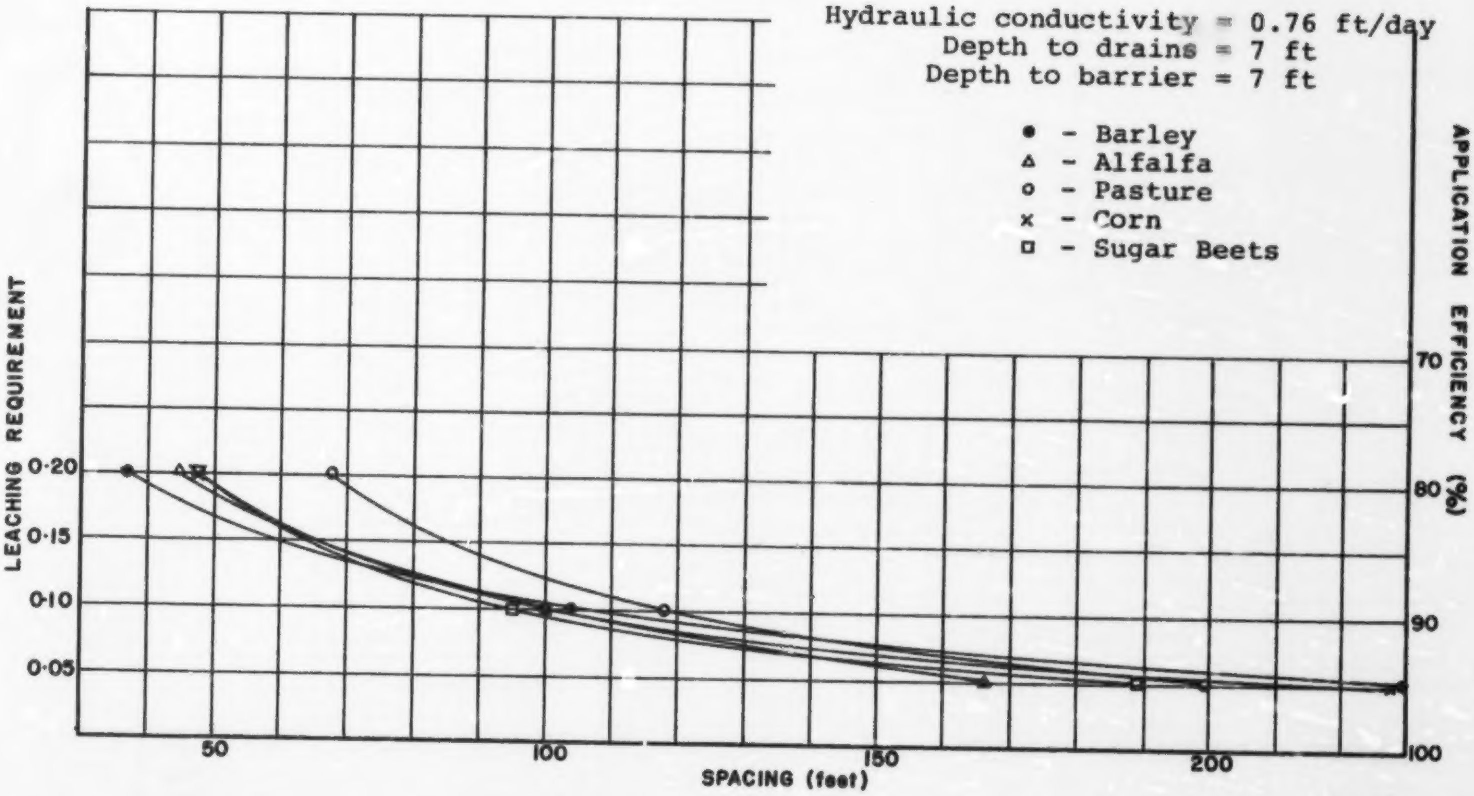


Figure 17. Relation between leaching requirement and drain spacing for the Canaday field.

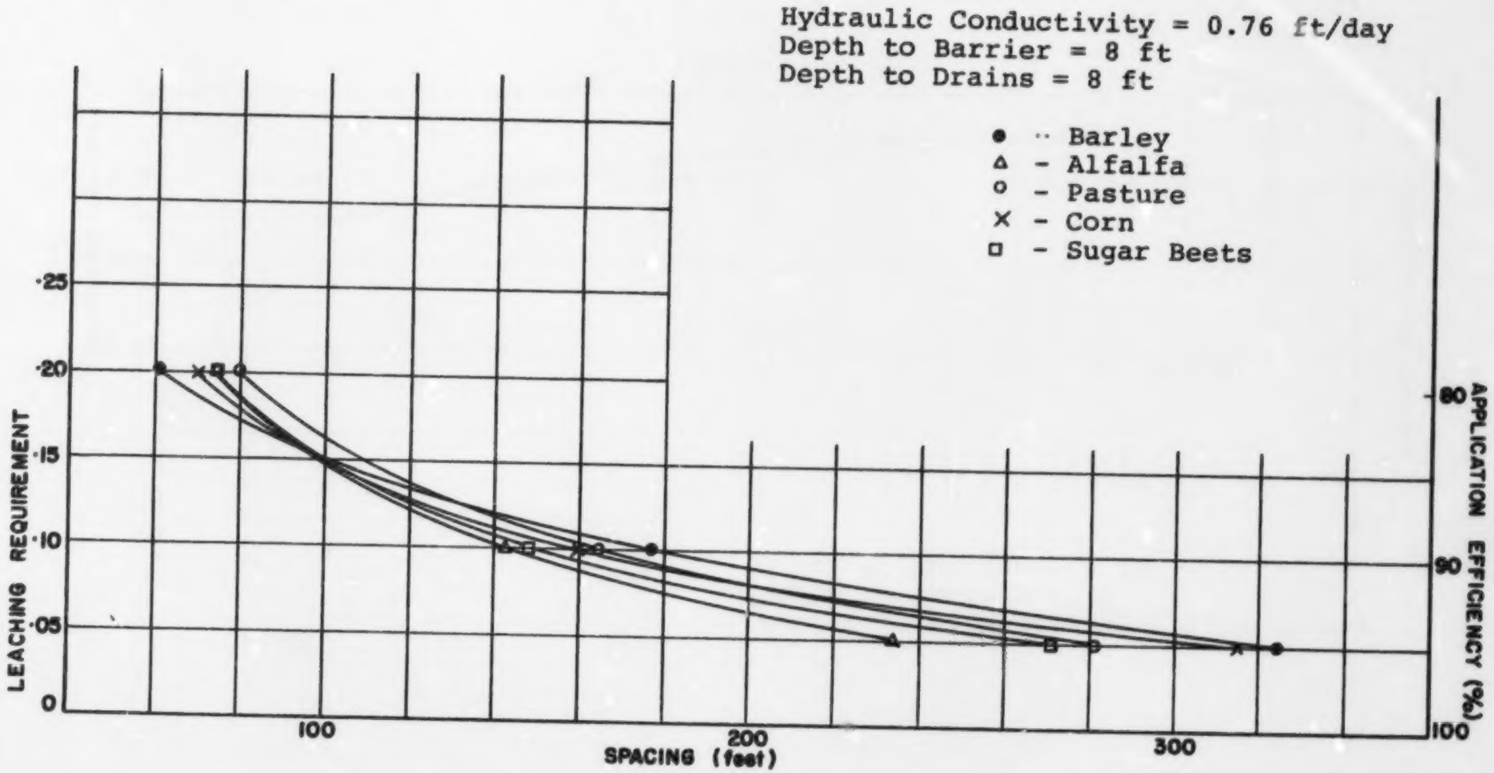


Figure 18. Relation between leaching requirement and drain spacing for the Kelleher field.

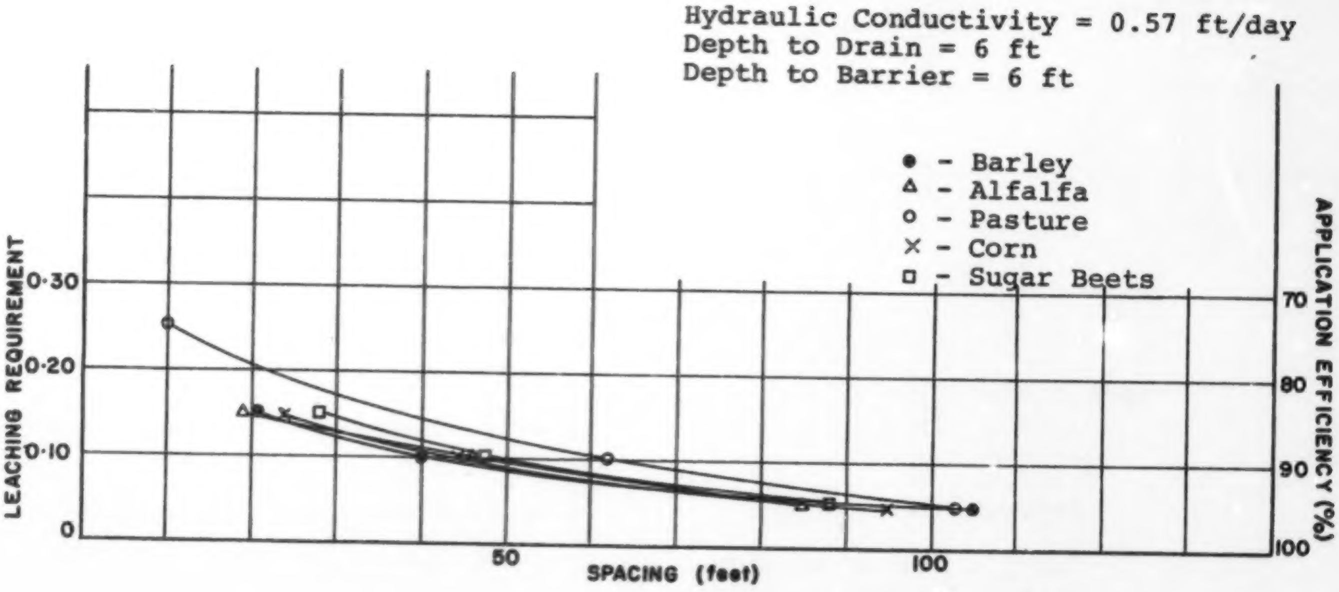


Figure 19. Relation between leaching requirement and drain spacing for the Wareham field.

Table 11. RESULTS OF IRRIGATION EFFICIENCY TESTS DURING THE 1972 IRRIGATION SEASON ON WAREHAM FIELD.

Irrigation Period	Field Inflow (inches)	Field Outflow (inches)	Net Application (inches)	Soil Moisture Storage Change (inches)	Crop Use (inches)	Percolation from the root zone (inches)	Application Efficiency[1] (%)	Irrigation Efficiency[2] (%)
6/12-6/28	9.12	4.56	4.56	0	1.09	3.47	24.0	11.9
8/ 3-8/10	14.76	5.13	9.63	+3.68	1.93	4.02	58.3	38.0

1. Application Efficiency = $\dfrac{\text{Crop use + soil moisture storage change}}{\text{Net Application}} \times 100$

2. Irrigation Efficiency = $\dfrac{\text{Crop use + soil moisture storage change}}{\text{Total Inflow}} \times 100$

Note: The water was turned on September 15, 1972 and allowed to run at will until October 30, 1972, which made it impossible to calculate water use efficiencies for this irrigation.

Drainage Design

The hydraulic conductivity on the Wareham farm used for design purposes was estimated to be 0.57 feet per day with the minimum depth to the clay barrier material being 6.0 feet. The leaching requirement was set at 8 mmhos/cm, the minimum permissible requirement needed to maintain the electrical conductivity of the soil in this field. Since the irrigation water has a typical value of abou 0.8 mmhos/cm, the leaching requirement is determined to be 10%. Based on these criteria, and using Figure 19, the drain spacing was estimated at about 40 feet (Ayars, 1972).

DRAINAGE SYSTEM CONSTRUCTION

The topographic map, Figure 13, indicated the direction of field slope and the direction the laterals and collector drains would be laid. Hence, the laterals were installed in the east-west direction and the collector drain in the north-south direction making an exit into the open drain in the southeast corner of the field as shown in Figure 20. The total length of pipe installed was approximately 11,500 feet.

During the early part of 1973, the pipe sizes were determined and ordered. The lateral lines were 4-inch diameter perforated plastic and the collector drain was 6-inch perforated plastic pipe. The pipe was a spiral design which allowed the pipes to be screwed together using special couplers.

Construction Activities

Construction began on May 14, 1973, with the Grand Junction Drainage District supplying labor, a track driven backhoe with a 30-inch bucket to make the excavation, a caterpillar tractor to cover the open trench, and a front-end loader to place the gravel used for the filter around the pipe.

The drain installation began by clearing strips of ground 20 feet wide on 40-foot centers in the field where grade lines and surface profiles were determined. The minimum grade on the lateral lines was 0.5%, while that of the collector drain was 0.4%.

The construction began by the excavation of the collector line starting at the drain outlet and proceeding into the field for a distance of 40 feet and then north along the east edge of the field stopping 40 feet from the north edge of the field. As this trench was to be left open for a period of time, it was benched to prevent any caving that may ordinarily occur. Stakes were driven on grade every 40 feet in the bottom of the trench and gravel placed to the top of the stakes. The 6-inch collector drain was then installed with a tee on 40-foot centers for the connection of the lateral lines.

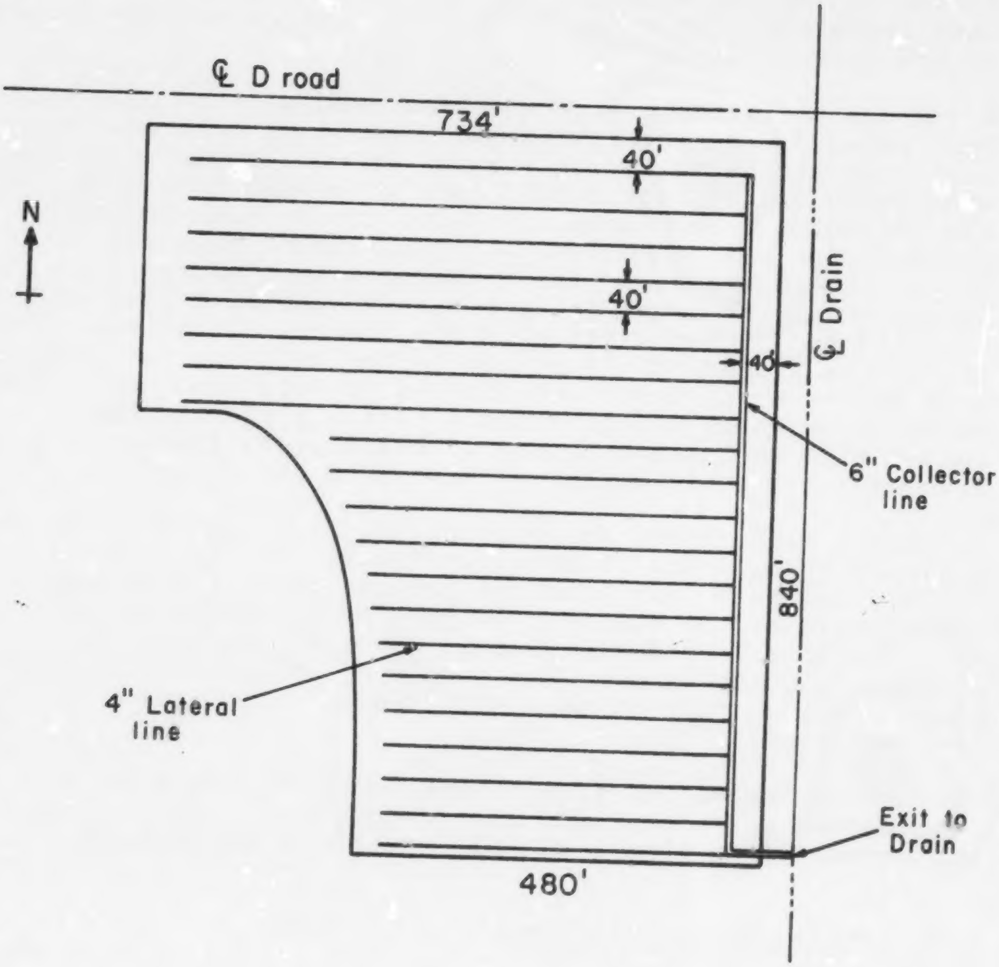
After the collector trench was excavated and the pipe laid, work began on the lateral lines. The lines were excavated beginning at the collector trench and moving west. As the excavation of the individual lines proceeded away from the collector trench some distance, the 4-inch perforated plastic pipe was connected to the collector pipe and laid in the lateral trench. The gravel was then poured into the trench using the front end loader with the fine grading accomplished by men working in the trench. After the gravel was placed, the pipe was lifted slightly to allow some gravel to go under the pipe to provide some permeable material on which the pipe could rest. A plastic sheet 4 inches wide was placed on top of the pipe to insure that no fine material would enter the pipe from the area above.

A typical cross-sectional view of the pipe, gravel, and plastic installation is shown in Figure 21. As soon as the plastic had been lain over the lateral pipe, gravel was then placed around the next 40 feet of collector drain between laterals and the plastic cover placed over the 6-inch collector line. Then both the lateral trench and the 40-foot section of collector trench were closed by the bulldozer.

The average amount of trench that could be excavated and pipe placed was about 1200 feet a day. The construction was completed on June 1 and all equipment was removed.

Post-construction Activities

After the drainage system had been installed, a tractor with a ripper implement was used to loosen the top 12 to 24 inches soil compacted by the construction. In addition, the construction had left mounds of unsettled earth overlying each trench which were consolidated by placing a furrow over the top of each trench and diverting water from the irrigation head ditch. The collector drain trench was difficult to settle because of the width with which it had been excavated and the difficulty in getting water into the furrow over the drain. Even with the problems of getting water to this trench, settlement was observed to have taken place along most of its length.



℄ D road
734'
40'
N
40'
40
℄ Drain
6" Collector line
840'
4" Lateral line
Exit to Drain
480'

Figure 20. Wareham farm drainage system layout.

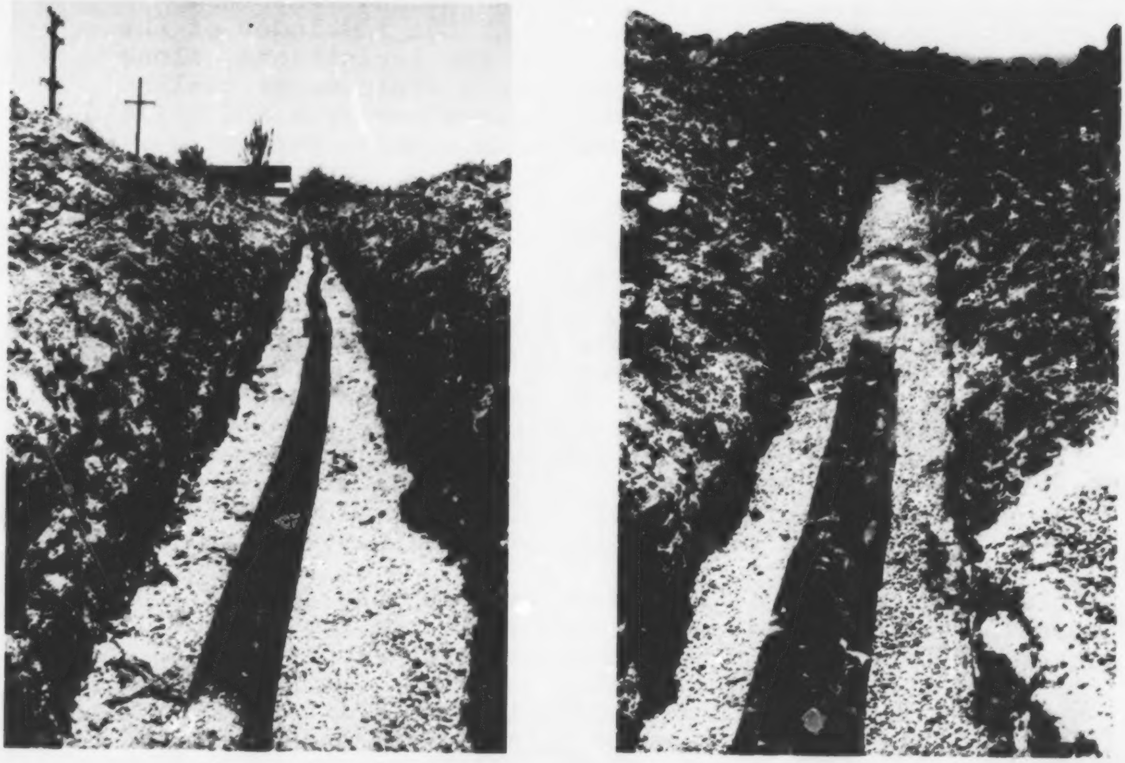


Figure 21. View of pipe installation.

Following the settling of the drain trenches, the field was planted to Jose Tall Wheatgrass with a cover crop of oats. While the grass is not a major cash crop, it is one of the most salt-tolerant and thus well suited to the Wareham field. In a few years this field should be reclaimed sufficiently to allow a higher cash value crop to be grown.

EVALUATION OF FIELD DRAINAGE

By the time planting of the Jose Tall Wheatgrass on the Wareham farm was completed, only two irrigations were required to sustain the crop through the remainder of the season. Data collected from these two irrigations, along with water quality samples taken from field water tables during the study, provided the information from which field drainage was evaluated as a salinity control measure.

Wareham Field Data

Several factors inherent in the field drainage on the Wareham farm require mention before the data are presented and analyzed. The upper soils on the farm were shown by soil salt analyses to be severely affected by poor water management in recent years. It was expected that the drainage effluents during initial tests would be laden with salts leached from the soil reservoir. As subsequent irrigations are made, the quality of the drain effluent will be expected to improve significantly, allowing the investment in the system to yield improved salinity control.

In another regard, it is almost certain that flows passing into the drainage system will come from the soil overlying the lines rather than any significant lateral movements. The field was badly compacted during previous years and during the drain installations. It is thus obvious that several years of careful land and water use will be necessary to improve the effectiveness of the drainage system. These factors lead to the conclusion that the real effectiveness of drainage should be determined over a much longer period. In fact, this same field will continue to be monitored during the 1974, 1975, and 1976 irrigation seasons as a part of the demonstration project "Implementation of Agricultural Salinity Control Technology in Grand Valley," which is being funded by EPA. However, because considerable data has been collected from this and other studies, significant observations can be made regarding local drainage.

During the irrigations on the Wareham farm, a careful program of water and salt budgeting was undertaken. This program, which was developed and utilized in several previous studies, also included measurements of a portion of the water percolating below the root zone when intercepted by the drain lines. The budgeting procedure incorporates inflow-outflow measurements with soil moisture readings and evapotranspiration estimates to delineate the individual flows. Generally, these data are presented in tabular form, but due to the limited number of budgeting intervals (two), the results in the Wareham field are presented graphically.

The water budget for the first irrigation is shown in Figure 22. Flow measuring flumes at both the inlet and exits determined that 12.8 acre-feet were added to the root zone (11.2 inches), of which 3.4 acre-feet were transpired by the crop (3 inches). Soil moisture samples at the beginning and end of the irrigation indicated that the soil reservoir moisture increased by 7.5 acre-feet (6.6 inches). The outflow from the drainage system was measured twice daily resulting in the hydrograph shown in Figure 23, which indicates about 0.25 acre-feet (0.2 inches) were actually intercepted by the drain lines. Comparing these flows indicates that 1.6 acre-feet (1.4 inches) percolated past the drains into the deeper groundwater. Again, it would seem that the poor condition of the soils limited the effectiveness of the drains.

The irrigations conducted by project personnel were designed to be as efficient as possible, although this practice may not have been representative of uncontrolled fields. Two measures of efficiency, farm efficiency and application efficiency, can be defined to indicate the degree of success achieved. Farm efficiency (FE) is calculated by dividing the sum of evapotranspiration (subtracting effective precipitation) and root zone soil moisture storage change by the water supplied to the field. Thus, FE = (3.4 ac-ft + 7.5 ac-ft)/21.6 ac-ft, or slightly over 50%. Application efficiency, which is the same as farm efficiency except that field tailwater is subtracted from the denominator, was 85%. Of the flows percolating into the area of the drain lines, only about 16% was actually intercepted. However, as stated before, this fraction should be significantly improved as the field comes under better management.

The data for the second irrigation, shown in Figure 24, indicate results similar to the first irrigation, except that the soils were already moist, resulting in a great deal more deep percolation. It is interesting to note that the drainage system did not remove significantly more water than during the first irrigation. These facts suggest

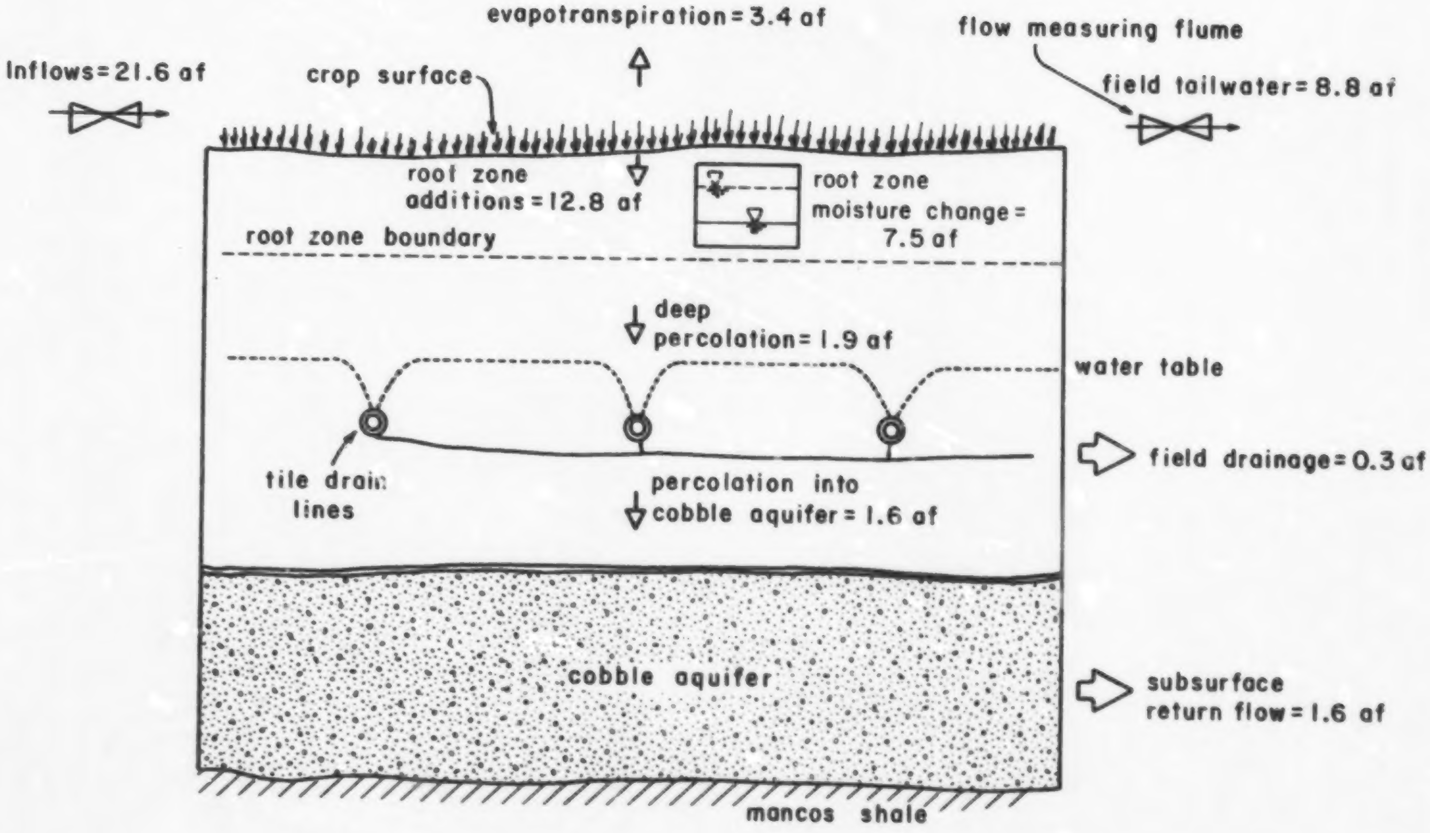

evapotranspiration = 3.4 af
flow measuring flume
Inflows = 21.6 af
crop surface
field tailwater = 8.8 af
root zone additions = 12.8 af
root zone moisture change = 7.5 af
root zone boundary
deep percolation = 1.9 af
water table
field drainage = 0.3 af
tile drain lines
percolation into cobble aquifer = 1.6 af
cobble aquifer
subsurface return flow = 1.6 af
mancos shale

Figure 22. Graphical water budget for the Wareham farm during its first irrigation after drain installation.

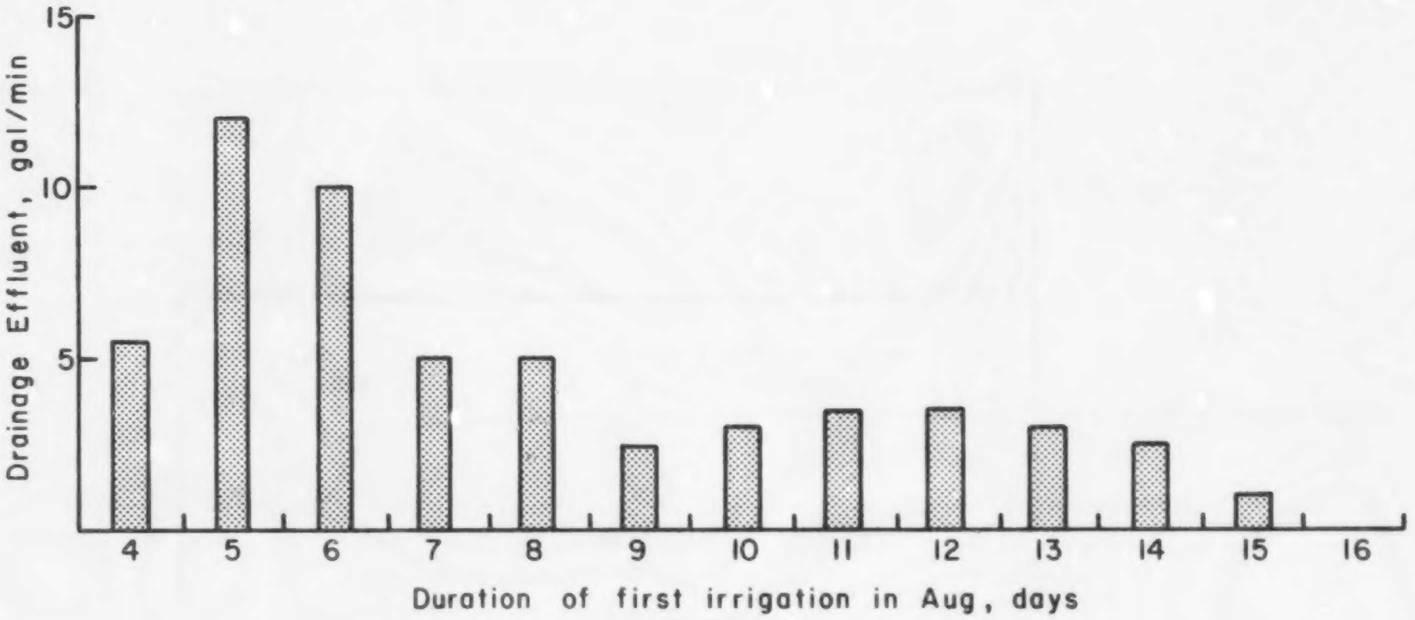


Figure 23. Average daily discharge from the Wareham farm drainage system during the first irrigation after installation.

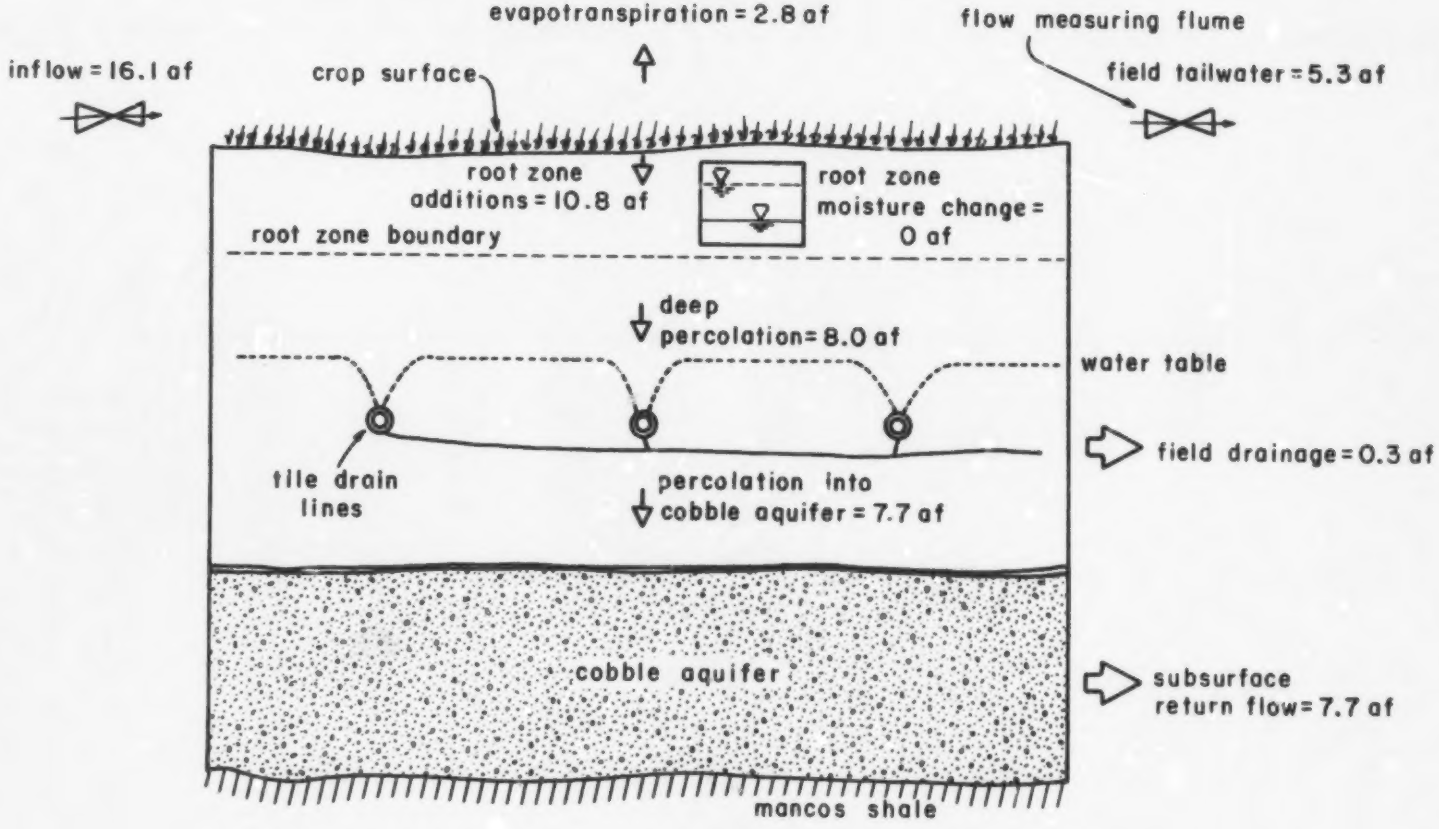

evapotranspiration = 2.8 af
flow measuring flume
inflow = 16.1 af
crop surface
field tailwater = 5.3 af
root zone
additions = 10.8 af
root zone
moisture change =
0 af
root zone boundary
deep
percolation = 8.0 af
water table
field drainage = 0.3 af
tile drain
lines
percolation into
cobble aquifer = 7.7 af
cobble aquifer
subsurface
return flow = 7.7 af
mancos shale

Figure 24. Graphical water budget for the Wareham farm during its second irrigation after drain installation.

that the spacing is too far apart. Hopefully, the reclamation of the field soils will improve drainage. The two measures of irrigation efficiency for this irrigation were 18% for farm efficiency and 26% for application efficiency, indicating a much poorer irrigation efficiency because of the already high level of soil moisture storage.

By applying average salinity concentrations measured throughout the field environs, a salt budget during each irrigation was determined as shown in Figures 25 and 26. It is interesting that the second irrigation, which was much less efficient, contributed more than seven times more salt to the return flow system than did the first. The concentration of salts leaving the drains during the first irrigation were 2440 ppm less than the second. Since the groundwater concentrations in this area are also about 7000-8000 ppm, the drainage system resulted in about 1 ton of salt reduction as compared to a field without drainage.

The values presented in Figures 25 and 26 are averaged from about 7-21 water quality analyses and do not necessarily reflect an important result. During the periods of high discharge from the drains, the quality is comparable to the nearby open drain, about 2000-4000 ppm. This would suggest that the high flows occurred from percolation immediately over the drains, where the soils had been disturbed.

Irrigation of the Wareham field during ensuing years will extend the sphere of influence of the drains to the entire field. When they become completely effective in this manner, the large quantity of salt contained in the soil profile will be leached. The salinity concentration in the profile at that time will approach the 4000-5000 mg/l level encountered in the better managed fields. At the present time, the concentrations of saturated extracts from soils on the Wareham field are between 13,000 and 17,000 mg/l. If existing data are indicative of the results to be expected in the future, it is possible to predict when the drainage system will have removed the excess salts from the soil profile. For example, if the annual application efficiency continues to be about 60%, then approximately twenty inches of deep percolation will be lost annually. Data describing the salinity concentration of flows intercepted by or passing beneath the drainage system reveals an average of about 5000-7000 ppm. The annual salt pickup can thus be computed as about 150 tons. If it is further assumed that the saturated extract represents most of the salts available in the soil, or at least depletes the storage to the point where the next extract sample would be no more than 5000 mg/l, then the salt tonnage to be removed by the drainage is about 350 tons, assuming also an effective porosity of 31% (Ayars, 1972). Thus, the reclamation of

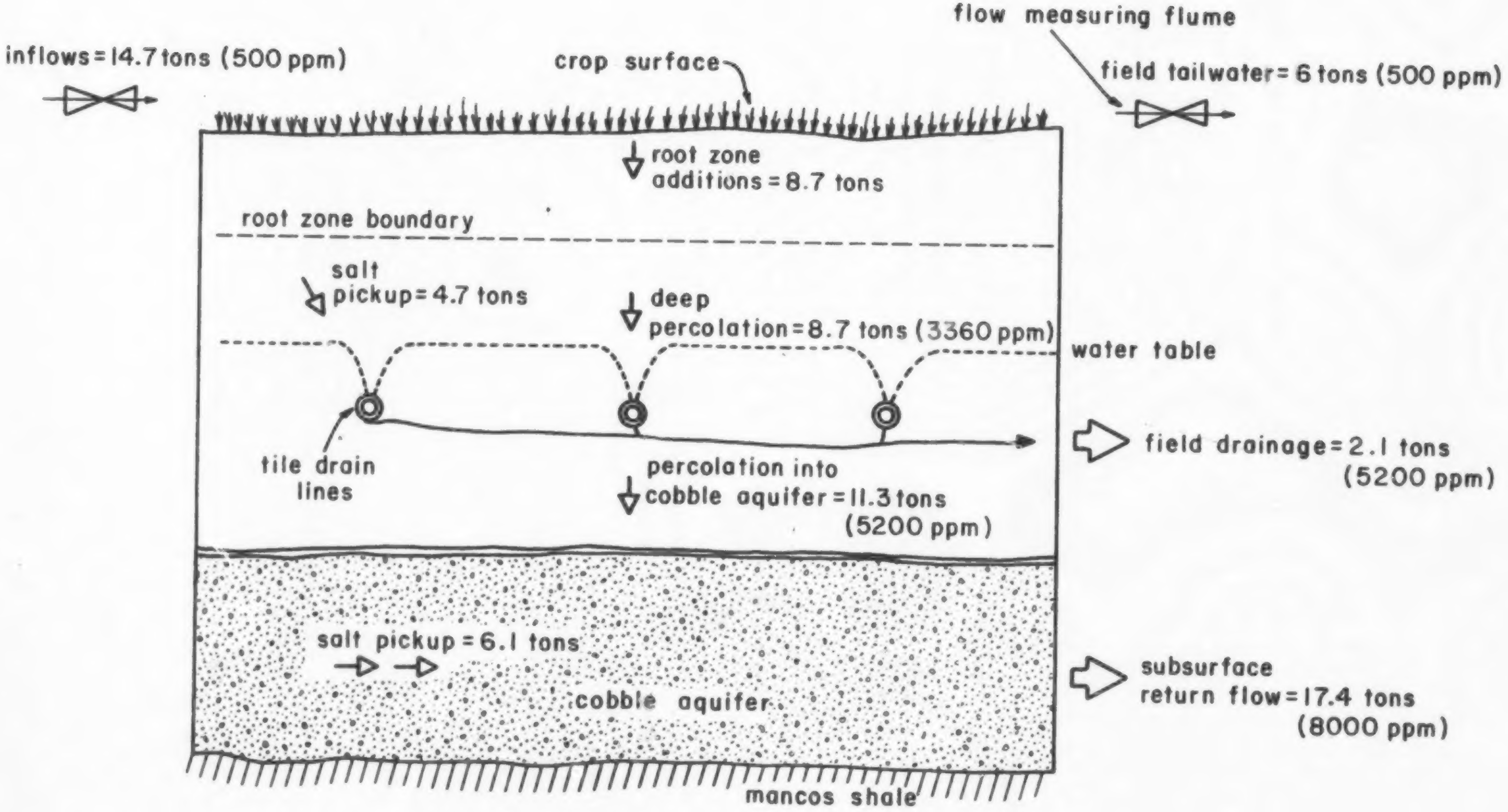

flow measuring flume
inflows = 14.7 tons (500 ppm)
crop surface
field tailwater = 6 tons (500 ppm)
root zone additions = 8.7 tons
root zone boundary
salt pickup = 4.7 tons
deep percolation = 8.7 tons (3360 ppm)
water table
tile drain lines
percolation into cobble aquifer = 11.3 tons (5200 ppm)
field drainage = 2.1 tons (5200 ppm)
salt pickup = 6.1 tons
cobble aquifer
subsurface return flow = 17.4 tons (8000 ppm)
mancos shale

Figure 25. Graphical salt budget for the Wareham farm during its first irrigation after drain installation.

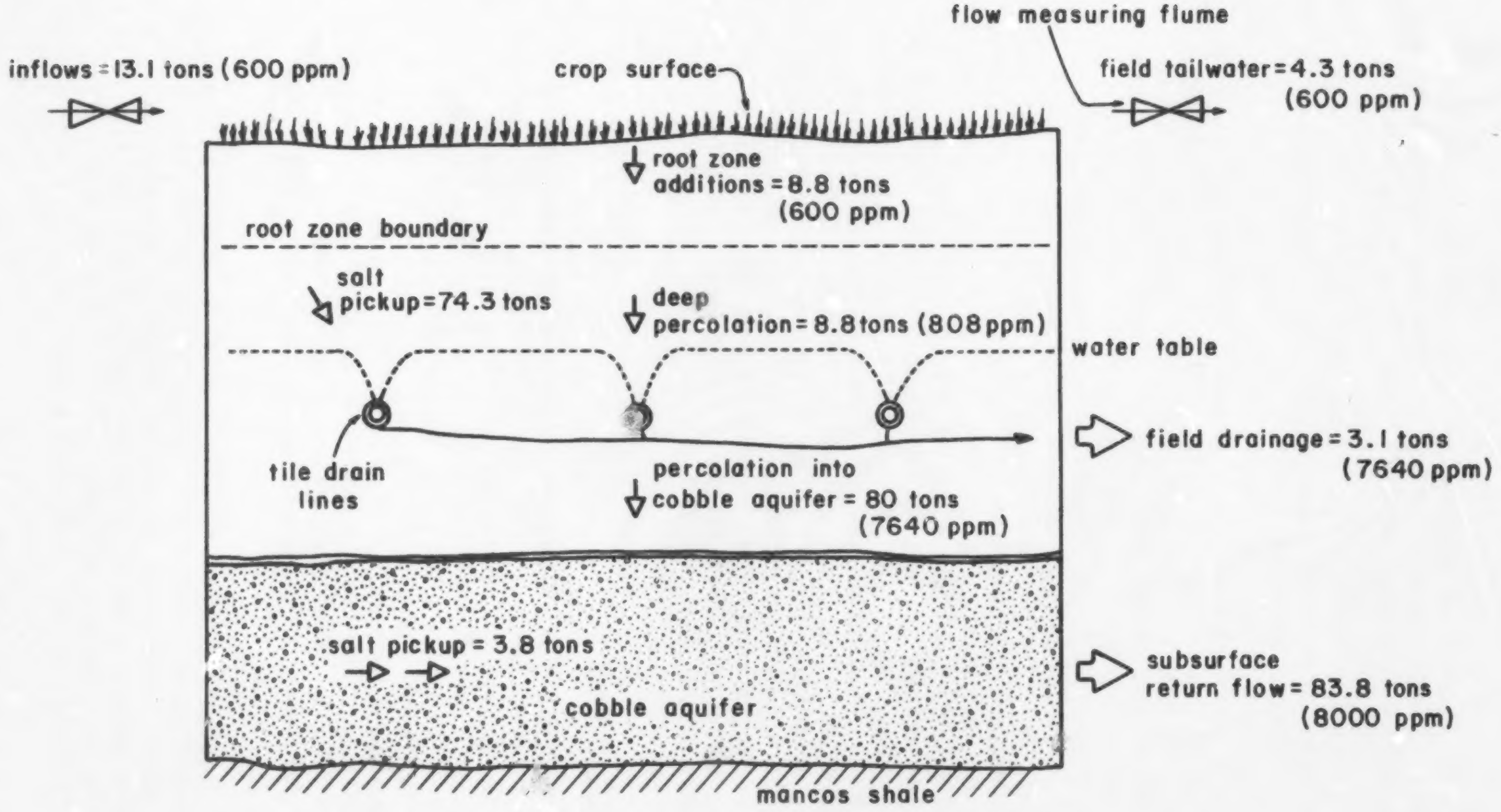

flow measuring flume
inflows = 13.1 tons (600 ppm)
crop surface
field tailwater = 4.3 tons (600 ppm)
root zone additions = 8.8 tons (600 ppm)
root zone boundary
salt pickup = 74.3 tons
deep percolation = 8.8 tons (808 ppm)
water table
field drainage = 3.1 tons (7640 ppm)
tile drain lines
percolation into cobble aquifer = 80 tons (7640 ppm)
salt pickup = 3.8 tons
cobble aquifer
subsurface return flow = 83.8 tons (8000 ppm)
mancos shale

Figure 26. Graphical salt budget for the Wareham farm during its second irrigation after drain installation.

the Wareham farm should be completed in about three irrigation seasons. These figures are, of course, crude estimates at this point because insufficient data have been collected. It could be safely assumed that salt leaching would be the greatest during the first few years. In the following irrigation seasons, more data will be obtained to substantiate these results.

To the reader of these results, the small effect of the drainage system on the Wareham farm probably raises doubts as to the value of such a salinity control measure. Questions arise regarding other special salt reducing measures, such as desalting, because of the high cost of reducing salinity. The importance of these measures, including field drainage, nevertheless exists in present salinity control technology. Each technique has associated with it an effect and a cost which generally changes in proportion to the amount of the source that has already been treated. Thus, an examination of the marginal costs with scale indicate that an optimal salinity control strategy involves even the most exotic treatments when the degree of required treatment becomes high. The evaluation of these factors and the development of such strategies is the subject of another research project, but it is these answers which are sought, not how well drainage or canal lining works. It is therefore important that the development of "what to do" be soundly based on "how to do", which is a major objective of projects such as this.

Analysis of Other Data

During the period of this project, samples of water were taken from the water table under several fields included in both the irrigation scheduling and drainage phases. Some of these data were presented in SECTION VI. Values of groundwater salinity generally exceed these data by 30 to 50%, indicating that significant salts are picked up beyond the farm environment. It should be noted that much of the salt in the upper soils is undoubtedly due to poor drainage and would be eventually leached. However, studies should be forthcoming to completely substantiate this conclusion.

The data from better managed fields indicate that field drainage has much more potential than indicated on the Wareham farm. However, the real need for field drainage is affected by the improvements in water management on the farm and in the conveyance system. This subject will be discussed separately in the following section.

SECTION VIII

DRAINAGE EVALUATION FOR GRAND VALLEY

The use of drainage systems in the Grand Valley for reducing the salinity of irrigation return flows requires that the groundwater be removed before it has reached chemical equilibrium with the underlying aquifers. Since these requirements restrict drainage methods to field relief systems, several questions regarding the feasibility of this program remain unanswered if improvements are made in conveyance and irrigation networks. Such questions include:

1. If conveyance and farm improvements are made, what will be the field drainage requirements?
2. Since pump drainage has been clearly demonstrated as the cheapest and more effective method, is it possible that treatment of these flows is a better strategy?
3. How are drainage or salinity control policies reflective of future changes such as urbanization, energy development, food and fibre needs, and social goals?
4. Will future technological advances view these decisions favorably?

Certainly, the results of this study do not answer these questions since they demonstrate only that some measure of salinity control is possible with relief drainage. In this section, the intent is to determine the effect which other salinity control measures will have on drainage requirements and test the feasibility of pump drainage in conjunction with desalination. To accomplish this task, limited as it will be by the lack of evidence, the first topic must be a definition of the local hydro-salinity system.

GRAND VALLEY HYDRO-SALINITY SYSTEM

Unfortunately, during a period of great concern for the problem of salinity in the Colorado River Basin, the impact of individual salinity sources is encompassed within the limits of measurement accuracy. In the Grand Valley area, the depletion from the Colorado and Gunnison Rivers, as well as the salt contributed by the area, is less than five percent of the mean annual flows. This allows those with limited vision and questionable competence to suggest the valley salt contributions and corresponding impacts of salinity control alternatives remain in question. Some insist that general data deficiencies preclude meaningful formulation of plans for local improvement or for justifying one project over another. A look at what can be said with existing data may be helpful.

There are two methods for establishing the impact an area has on water and salt flows. The first is the input-output model alluded to above and the second is hydro-salinity modeling of the internal water uses.

Input-Output Analysis

Inflows to the Grand Valley occur as flows in the Colorado River, Gunnison River, and precipitation. In addition, a small quantity of water is imported for domestic and industrial purposes, and a possibility exists that precipitation on the watershed adjacent to the valley may contribute via diffuse groundwater inflows. Neither of these latter flows are deemed significant, especially the inflow from surrounding lands because of the low annual precipitation (8-10 inches) and high evaporative demands (40-45 inches).

As a means of better identification, data for the 1968 water year from the U.S. Geological Survey (USGS) and U.S. Weather Bureau can be utilized. Inflows passing the USGS gaging stations "Colorado River near Cameo" (2,413,000 acre-feet), "Plateau Creek near Cameo" (112,000 acre-feet), and "Gunnison River near Grand Junction" (1,444,000 acre-feet) totaled 3,968,000 acre-feet carrying an estimated salt load of 3,070,500 tons. The outflows passing the station "Colorado River at Colo-Utah State Line" totaled 3,722,000 acre-feet and approximately 3,771,000 tons of salt. These figures represent either published data or interpolations thereof. It should be noted that the state line station collects only limited quality data.

A comparison of the inflows and outflows indicates that 246,000 acre-feet of water were depleted from the system and 701,000 tons of salt added. Precipitation records indicate that approximately 75,000 acre-feet fell on the land encompassed by the irrigated boundaries of which it is estimated that 25,000 acre-feet could be classed as "effective on the irrigated acreages." These estimates are congruent with similar computations presented by Iorns, et al. (1965), Hyatt (1970), U.S. Environmental Protection Agency (1971).

Another check on these numbers can be made from land use data collected by Walker and Skogerboe (1971) which was summarized earlier in Figure 4. A somewhat more definitive breakdown is presented in Table 12. Westesen (1974) estimated that the consumptive use based on the pan evaporation data from the U.S. Weather Bureau and calculations using the Modified Jensen-Haise method amounted to about 295,000 acre-feet annually, including almost 25,000 acre-feet of effective precipitation on other vegetative uses. Thus, the inflow-outflow data for this particular year regarding water flow is acceptable. An examination of the salt flows will be noted for comparison in the following paragraphs.

Table 12. AGRICULTURAL LAND USE IN THE GRAND VALLEY.

Land Use	Acreage	Percent of Total
Irrigated	60,844	53
Idle	9,706	8.5
Dwelling & Premises	10,678	9.3
Open Water	1,699	1.5
Phreatophyte	15,174	13.2
Natural Terrain	16,607	14.5
Total [1]	114,708	100.0

[1] Roads and railways have been omitted.

Hydro-Salinity Budgeting

The second approach to establishing the effects of water use in the Grand Valley is to model the complex interrelationships associated with irrigation and drainage. Several parameters are added to the analysis to account for the various flows which take place.

The first segment encountered is the delineation of the canal diversions. As the water is diverted from the rivers into the canals and ditches, a certain portion of the flow seeps or evaporates from the conveyance surfaces, while still another fraction is spilled into wasteways as a means of regulating capacity. The remainder of the flow is diverted through small headgates into an extensive lateral system leading to the fields. It is important in this type of analysis that each flow path be defined, because each results in a different salinity effect. For example, the evaporative losses concentrate the salts in the remaining flows, whereas the seepage enters the saline groundwater basin and results in salt pickup.

Lateral diversions eventually become seepage, field tailwater, root zone additions or evaporation, as was the case above. In a similar manner, the root zone additions result in cropland consumptive use or deep percolation. When deep percolation is combined with seepage losses, a groundwater flow segment is begun which results in the severe salt loadings common in the valley. A great deal of the groundwater is consumed by water-loving phreatophytes abundant in the area and some of the flows are intercepted by the open-ditch drainage system. A substantial amount returns to the rivers through aquifers making precise measurement difficult.

Westesen (1974) examined the 1968 water year in some detail and combined many of the principles discussed by Walker (1970) into an accounting of the flows derived for irrigation in the Grand Valley. His results, shown in Tables 13, 14, and 15, compare very well with data collected by the authors in recent years.

Interpretation of Data

The budgets contained in Tables 13, 14, and 15 include some important insights to the water use practices in the Grand Valley. It has generally been the practice to state the results of budgeting procedures in terms of efficiencies, in order to extend the conclusions to other areas. Most notable, efficiencies such as conveyance efficiency, irrigation efficiency, etc. are commonly found in the literature. Since a great deal of variation can be found in the specific definitions of these terms, the following paragraphs will define a term and discuss its value in the Grand Valley.

Possibly the most general measure of how well water is utilized in an agricultural area could be termed regional irrigation efficiency. If irrigation efficiency is defined as the percentage of the total diversions which are beneficially used by crops, then from Table 15 it can be seen that for the Grand Valley an efficiency of about 27% will

Table 13. GRAND VALLEY WATER BUDGET FOR 1968 WATER YEAR.

Budget Item		Acre-Feet
Surface Inflows		
Colorado River near Cameo, Colorado		2,413,000
Plateau Creek near Cameo, Colorado		112,000
Gunnison River near Grand Junction, Colorado		1,443,000
	Total	3,968,000
Effective Precipitation		
Cropland		25,000
Phreatophytes		5,400
	Total	30,400
System Depletions		
Water Surface Evaporation		
Canals		8,000
Rivers		8,000
Phreatophyte Consumption		
Along Canals and Drains		64,000
Adjacent to Rivers		21,400
Cropland Consumption		175,000
	Total	276,400
Surface Outflows		
Colorado River at Colorado-Utah State Line		3,722,000

Table 14. GRAND VALLEY DISTRIBUTION OF CANAL FLOWS IN 1968.

Budget Item	Acre-Feet		Acre-Feet
Canal Diversions	560,000		
Spillage			103,000
Seepage			25,000
Evaporation			8,000
Lateral Diversions			424,000
		Total	560,000
Lateral Diversions	424,000		
Seepage			51,000
Field Tailwater			162,000
Root Zone Diversions			211,000
		Total	424,000
Root Zone Diversions	211,000		
Evapotranspiration			150,000
Deep Percolation			61,000
		Total	236,000
Groundwater Return Flows	137,000		
Phreatophyte Consumption			60,000
Subsurface and Drain Flows			77,000
		Total	137,000

Table 15. SALT BUDGET FOR GRAND VALLEY DURING 1968.

Budget Item	Flow (acre-feet)	Concentration (ppm)	Salt Load (tons)
Inflows			
Colorado River near Cameo	2,413,000	454	1,490,000
Plateau Creek near Cameo	112,000	454	69,000
Gunnison River near Grand Jct.	1,443,000	769	1,511,000
		Total	3,070,000
Outflows			
Colorado River near Colo-Utah State Line	3,722,000	745	3,771,000
Salt Pickup			701,000

be realized. This efficiency is determined by dividing the cropland consumption minus effective precipitation by the canal diversions. To improve irrigation efficiency, several management practices and structural improvements could be made by canal companies and irrigation districts. For example, by eliminating spillage in the system as a means of capacity management and replacing it by call periods and diversion regulation, the efficiency could be increased by 18% to more than 45%. Canal linings would further enhance this measure to almost 50%. The other available improvements are largely of an individual nature depending on the care and control of water by the irrigators.

Associated with the irrigation efficiency noted above are two more specific measures of conveyance efficiency. Canal conveyance efficiency and lateral conveyence efficiency may be taken as the percentages of the carried flows which reached the intended destinations. In the valley, the efficiencies of both systems are 94% and 88%, respectively.

Once the flows reach the lateral and farm ditch systems, it is possible to attach an efficiency measure to the irrigators themselves. Skogerboe and Walker (1972a) define farm efficiency as the percentage of water availalbe to the farm which is consumptively used. Thus, farm efficiency is approximately 35%. This value can also be significantly improved by better water management. Specifically, the minimization of field tailwater and lateral linings could potentially increase farm efficiency to 86%. Certainly, a reasonable figure would be 60-70% if effective programs were undertaken.

Probably the most important measure of efficiency with respect to salinity control is termed application efficiency. This value represents the fraction of the flows applied to the root zone reservoir that is utilized by the crops. Its importance is that deep percolation is directly evaluated. In the Grand Valley, an average value of application efficiency is about 71%. The most significant improvement to this value can be made through a coordinated and effective irrigation scheduling program.

Although other conclusions can be drawn from these budgets, the preceding discussion will serve the following examination of drainage alternatives.

IMPACT OF WATER MANAGEMENT ON DRAINAGE

The water and salt flows for the 1968 Water Year are typical of results presented by several investigators such as Iorns, et al. (1965), Hyatt (1970), and the U.S. Environmental Protection Agency (1971). The important budget parameter, salt pickup, is currently a topic of wide discussion, but its value for the Grand Valley can be expected to vary between 0.5 and 1.0 million tons of salt annually. In the opinion of the authors after several years of detailed study of the Grand Valley area, the variation in salt pickup is probably due primarily to the available data rather than periodic changes in water use practices.

With these budget data as the basis, it is interesting to examine the need for field drainage as improvements become implemented in the irrigation system. Such local improvements as canal linings, lateral linings, and better on-farm water management (irrigation scheduling in its total perspective, which includes on-farm irrigation improvements) will affect water table levels by significantly reducing the groundwater inflows and thus easing the demand on the natural drainage mechanisms. Several examples may demonstrate this point. In 1970, a canal and lateral lining program was undertaken as part of an earlier phase of this project with the results reported by Skogerboe and Walker (1972a). Several farmers below the Mesa County Ditch have since related to the authors that the linings seemed to lower local water tables and significantly improve their lands. Another example occurred as a part of a small lateral lining project further west by the Soil Conservation Service ASCS program in which nearby water tables were lowered several feet. Such examples are commonly reported in the Grand Valley area and are considered the basis for suggesting conveyance channel linings may be a partial solution to salinity.

One other aspect of the Grand Valley condition that should be mentioned. The cobble aquifer underlying (one-half) of the valley is on the order of 10^3 to 10^4 more permeable than the soils, yet the hydraulic gradients are quite comparable. The obvious conclusion must be that most irrigation return flows passing through the groundwater system are occurring as flow in this aquifer. As a result, most flows from seepage or deep percolation are moving downward rather than laterally. A notable exception exists when the leaky aquifer develops a vertical gradient and supplies water to the upper water table.

The previously noted conditions suggest that much of the local water table problems are due to over-irrigation, especially along the higher northern lands in the area. Lower areas and isolated trouble spots are affected by excessive groundwater flows trying to leave the area. If the local canals and laterals were lined (including farm head ditches), Table 14 indicates that 77,000 acre-feet annually, which amounts to 55% of the groundwater inputs, would be prevented from contributing to local drainage problems. (If only the canals were lined, the groundwater would be decreased by only 18%). Such improvements may also reduce the evapotranspiration from phreatophytes and result in significant water savings as well. Canal linings appear to be the initial program for controlling salinity in the Grand Valley although it is the least effective alternative available.

Probably the greatest potential for salinity control lies in on-farm water management which directly includes the lateral conveyance system. Together, deep percolation and lateral seepage contribute 82% of the groundwater flows. If effective irrigation scheduling programs are incorporated locally, which means accompanying the scheduling services with rehabilitation of the irrigation systems, the need for field drainage will be diminished.

Thus, the first steps in a salinity control program are to minimize: (a) seepage losses from canals and laterals; and (b) deep percolation losses from croplands (ideally, the deep percolation losses would not exceed the leaching requirement). By minimizing the amount of moisture reaching the groundwater, the requirements for field drainage will also be minimized. As higher levels of salinity reduction are sought, field drainage becomes a more feasible component of a valley-wide salinity control program.

PUMP DRAINAGE AND DESALINATION

The development of salinity control technology to date has been exclusively oriented towards preventing the flows from contacting saline soils and aquifers. An alternative approach would be to simply treat the salt ladened irrigation return flows. Such a program in the Grand Valley area could either be through a system of field relief drains intercepting the downward flows or pump drainage, both of which would be collected and desalted.

Desalting Technology

The technology of desalting brackish waters, or even highly mineralized sea water, is developing at an exciting rate. However, until recently, its use has been primarily to produce high quality water rather than treat brackish flows to amend regional salinity problems. For waters having salinity concentrations between 2,000 and 10,000 ppm, the two most feasible desalination processes are reverse osmosis and electrodialysis. Desalination plants of this nature have generally indicated some economy with scale and have, therefore, tended to be large. Small plants with capacities up to 10 cfs show only slight economies with scale, and since such plants are likely to be more applicable in the Grand Valley, their cost can be assumed high. A more detailed analysis is beyond the scope or intention of this report.

The costs of treating the groundwater flows, such as those in the Grand Valley, are reported to be on the order of $150 per acre-foot. Thus, for the local groundwater, the costs per ton of salt removed would be about $15 per ton of salt removed assuming a product water with 500 ppm. This figure agrees generally with data reported by Westesen (1974).

Desalting Pump Drainage Effluents

The earlier review of pump drainage experiments in the Grand Valley indicated that the wells affected an area up to one-half mile in diameter with a discharge of less than 280 gallons per minute (0.56 cfs). To pump significantly more than this quantity of groundwater would have exceeded the inflow to the well area. As a result, to establish a 10 cfs flow into a desalination plant would require a considerable collection and conveyance system. Plants larger than 10 cfs would not likely be utilized in the Grand Valley since the economies of scale would be more than offset by the transmission costs. Thus, desalting drainage effluents in the area could be expected to remove salts for about $15 per ton plus pumping and transport costs, which may amount to less than $5/ton (Westesen, 1974).

Table 14 points out that the 77,000 acre-feet of groundwater return flow contributes 701,000 tons of additional salts to the Colorado River. The use of pump drainage and desalting in controlling this salt loading depends on the relative feasibility of improving the elements of the irrigation system. As a basis for comparison, the annual costs of collecting and treating the groundwater at an assumed rate of $17 per ton of salt removed are about $12 million. Westesen (1974) derives cost functions for canal linings, lateral linings, and on-farm improvements and then optimizes these functions to arrive at optimal dollar investments to achieve various degrees of salt loading reductions in the Grand Valley. This analysis indicates an annual cost of $5.4 million (6-7/8% interest and 50 year repayment period) to achieve a maximum reduction of 582,000 tons by reducing canal seepage by 15,000 acre-feet, lateral seepage by 33,000 acre-feet, and on-farm deep percolation by 54,900 acre-feet. The additions to the groundwater from canal and lateral seepage after linings would produce 163,000 tons of salt pickup, whereas the deep percolation from the crop lands amounting to 4% leaching would be more saline than the groundwater and therefore pickup no salt. Thus, if the remaining 163,000 tons of salt were removed through desalting, ($1.8 million annual cost), the costs would be $7.2 million annually ($5.4 million plus $1.8 million) to produce a zero salinity discharge from the Grand Valley. It can thus be seen, that desalting drainage flows is necessary to achieve zero discharge, but in a gradually implemented salinity control program, it is likely to be added after much of the irrigation system is improved. It should be noted, however, that the point where such use of desalting of irrigation return flows is made should be determined by a more exhaustive analysis.

SECTION IX

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SECTION XI

LIST OF SYMBOLS AND EQUIVALENTS

Symbol	Definition
CS	canal seepage, acre-feet
d,D	saturated depth below drains, ft
d	depth of water table below auger hole, ft
D_{cw}	depth of evapotranspiration, in
D_{dw}	depth of drainage water, in
D_{iw}	depth of irrigation water, in
DR	drainage outflow, acre-feet
EC_{dw}	specific conductance of drainage water, μmhos/cm
EC_{iw}	specific conductance of irrigation water, μmhos/cm
E_{ta}	potential evapotranspiration from well-watered alfalfa, cal cm^{-2} day^{-1}
ET_c	evapotranspiration by agricultural crops, acre-feet
GW_a	groundwater inflows from artesian aquifers, acre-feet
GW_d	downward drainage to pumped aquifer, acre-feet
GW_{io}	net groundwater inflow, or outflow from adjacent areas, acre-feet
GWS	groundwater storage change, acre-feet
h	water table height above drains, ft
h_m	water table height at the midpoint between drains, ft
H	initial saturated thickness of aquifer at midpoint between drains, ft
H_k	equivalent permeable height above water table, ft
H_s	equivalent saturated height above water table, ft
i	hydraulic gradient ft/ft
IR	deep percolation, acre-feet
K	Hydraulic Conductivity, in/hr

Symbol	Definition
P	precipitation, acre-feet
Q	volumetric flux rate, cfs
R_s	solar radiation, cal cm^{-2} day^{-1}
s	distance from bottom of the auger hole to the impermeable boundary,ft
S,X,L	distance between drains, ft
t	measure of various times, days, hrs
T	temperature,°F
T_x, C_t, C_1, C_2, C_H	regional constants
w	uniform recharge rate, in/day
y	distance from static water table to elevation of water in auger hole,ft
y_o	total depth of drawdown in auger hole, ft
Y_k	equivalent permeable thickness of aquifer, ft
Y_s	equivalent saturated thickness of aquifer, ft
Y_{xt}	height of water table at a distance from drains at time t, ft
z,Y	saturated thickness of aquifer, ft
z_a	height above water table where adequate soil aeration exists, ft
α	diffusivity, m-ft/hr
$\phi d',s$	specific yield, %
ϕ_e	effective porosity

ENGLISH-METRIC EQUIVALENTS

1 inch = 2.54 centimeters
1 foot = 0.3048 meters
1 acre-foot = 1,233.62 cubic meters
1 cubic foot per second = 0.02832 cubic meters per second
1 gallon (U.S.) per minute = 0.06308 liters per second
1 degree Fahrenheit = 5/9 degrees centigrade